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TRACTION CHARACTERISTICS OF AN ALBERTA SOIL

by
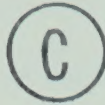
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A THESIS

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The undersigned certify that they have read, and recommend
to the Faculty of Graduate Studies and Research, for acceptance, a
thesis entitled " Traction Characteristics of an Alberta Soil"
submitted by Subhash Mehra in partial fulfilment of the requirements
for the degree of Master of Science.

ABSTRACT

An Alberta soil (Malmo silty-clay loam) was characterized for
traction. A standard agricultural tractor (Massey Ferguson 135) with
14.9-24 rear tires was instrumented for torque, pull, weight transfer,
rear wheel speed and actual forward speed measurements. The following
soil physical properties were measured; cohesion, angle of internal
friction, cone index, density and moisture content.

A device-soil system was tested which related device and soil
parameters. The clay mobility number $(Cbd/W.(\delta/h)^{1/2}. 1/(1 + b/2d))$
developed by the United States Waterways Experiment Station (WES) for
circular and rectangular-section tires in clay can be used to predict
performance in the Alberta soil tested.

The effect of ballast and surface conditions were studied for their
effect on the coefficient of traction. The surface conditions were
grass, stubble and fallow surface. The coefficient of traction
(performance parameter) was evaluated statistically by an analysis of
covariance at 36% slip. The coefficient of traction decreased with an
increase in ballast on the grass and stubble fields. On fallow there
was an increase in the coefficient with an increase in ballast. There
was no significant difference in the traction characteristics between
stubble and grass surfaces. Within the speed range used, speed had
little effect on the coefficient of traction.

ACKNOWLEDGEMENT

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1. A — Contact area

2. A_a — Soil-material adhesion

3. A_1 — Distance, per revolution without pull

4. b — Width of tire

5. B_1 — Distance, per revolution with pull

6. b_c — Compressibility coefficient (Bailey)

7. C — Cone index

8. c — Soil cohesion

9. C_r — Relative penetration resistance

10. d — Diameter

11. E — Modulus of elasticity

12. G — Penetration resistance gradient

13. g — Acceleration due to gravity

14. H — Soil thrust (soil reaction)

15. Hmax — Maximum traction

16. h — Section height of tire

17. i or s — Slip %

18. j — Soil deformation in the horizontal direction

19. k — Shear deformation modulus

20. k_c — Plate penetration modulus (Bekker)

21. k_c' — Plate penetration modulus (Reece)

22. $\bar{k}_\phi$ — Plate penetration modulus (Bekker)

23. k'_ϕ — Plate penetration modulus (Reece)

24. l — Length of device in contact with the surface

25. m — Compressibility coefficient (Bailey)

26. n — Plate penetration modulus (Bekker)

27. n' Plate penetration modulus (Reece)

28. n_c Compressibility coefficient (Bailey)

29. η_{tr} Tractive efficiency

30. P Net pull

31. p Pressure normal to the shear plane

32. PR Penetration resistance

33. P_T or R_r Rolling resistance

34. Q Resultant soil reaction

35. qu Unconfined compression strength

36. R Modulus of rupture

37. r Grain size

38. r_o Rolling radius at zero slip

39. r_a Active rolling radius

40. S Shear strength

41. $Smax$ Maximum shear stress

42. T Axle torque on wheel

43. T_S Tensile strength

44. v Forward velocity

45. W Weight on wheels, at the axle

46. $W.T.$ Weight transfer

47. x Horizontal displacement

48. Z Sinkage

49. ϕ Soil friction angle, angle of shear resistance

50. ρ Coefficient of rolling resistance

51. μ Coefficient of net traction

52. μ_T Coefficient of gross traction

53. δ Deflection in tire

54. δ_1 Soil material friction angle

55. ρ_d Density

56. γ Wet unit weight

57. σ Stress

58. ω Angular velocity

59. ω_o Angular velocity at zero slip

1. INTRODUCTION

1.1   The Problem.

The world today is a wheeled world. With each passing year, twentieth century man finds more and more ways to use the off-road travel capability of wheeled vehicles. Agricultural applications, timber harvesting, exploration and development of oil, gas, and mineral fields and many other activities depend, in part, on choosing the proper vehicle equipped with tires of proper size, shape and construction.

Soils and their surface conditions are primary factors affecting traction. There is a great need for studies of traction device-design to relate traction to soil conditions. It is fortunate that most device-design factors which improve traction on one soil condition also improve traction on other soil conditions. However, the need exists for determining accurately the soil conditions relating to design. For traction performance on agricultural soils, a device-soil system should be developed which relates device and soil parameters.

1.2   Purpose and Scope of this Study.

The primary purpose of this study was to develop a performance prediction capability for agricultural tires (pneumatic tires) on an Alberta soil by an empirical relation. The soil should be characterized from the traction point of view so that manufacturers and farmers can utilize the data for predicting the performance of tractors in the field.

The performance of a pneumatic wheel on a deformeable soil depends upon four factors (10,20). These are:

      a.   the strength of the soil,

      b.   the load on the wheel,

      c.   the geometric characteristics of the tire, and

d.   the speed, both of rotation and of advance,

of the wheel.

Speed was considered for this study even though speed is assumed to

have little effect on experimental results (8).

2. TRACTION-WHEEL FORCE SYSTEM

Traction is the term applied to the driving force developed by a wheel or other traction device. Traction is developed through forces acting in the mutual contact surface of the traction device and the medium on which it is operating.

The soil-wheel system can be considered from an energy standpoint as follows (26).

Power Input (traction device) = Power Output (Drawbar)

+ Losses.

The losses result from slip, front wheel rolling resistance and rear wheel rolling resistance.

Rolling resistance losses are due to tire flexure, soil-wheel friction, compaction, flow and bulldozing of the soil(22).

Zero slip can be determined at zero torque of the wheels (towed state) or at zero pull of the wheels (self-propelled state). For this study zero slip was determined at zero torque. Usually slip in the equation form is presented as:

$$\text{Slip (\%)} \qquad s = \frac{(A_1 - B_1)}{A_1} \; 100$$

where,

A_1 = distance, per revolution without pull.

B_1 = distance, per revolution with pull.

The traction of a wheel is best described by Persson (cited by Domier (6)) who used the following parameters (figure 1).

The coefficient of gross traction $\mu_T = \frac{1}{W} \frac{T}{r_o} = \frac{H}{W}$

The coefficient of net traction $\mu = \frac{P}{W}$
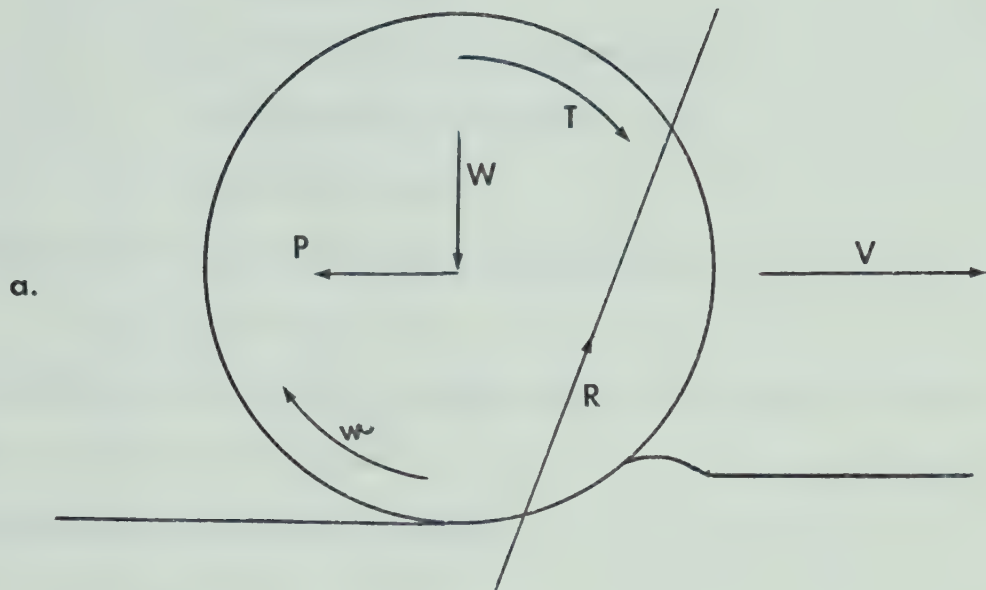
Figure 1 : a) Basic velocities and forces on wheel.
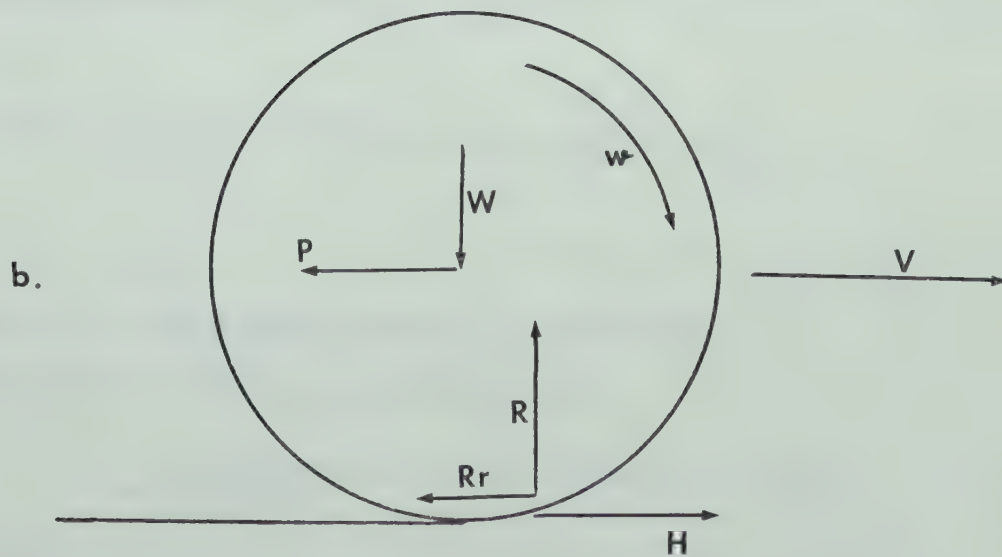
Figure 1 : b) Gross traction concept.

where,

W = weight on wheels, at the axle.

P = the net pull.

r_o = rolling radius at zero slip.

T = axle torque on wheel.

H = soil thrust.

Rolling resistance of the tire is defined as:

$$R_r = \frac{T}{r_o} - P = H - P.$$

The coefficient of rolling resistance ρ is the ratio of rolling resistance and the vertical load.

The following relationship exists

$$\mu = \mu_T - \rho.$$

The forward velocity of a powered wheel is

$$v = r_o \, \omega(1 - s)$$

where ω is the angular velocity and s is the slip.

Other performance parameters are derived from the basic parameters. These are:

Tractive power coefficient $(\pi) = \dfrac{Pv\omega_o}{W v_o \omega} = \dfrac{Pv}{W r_o \omega}.$

$$= \mu(1 - s) = \mu_T(1 - \frac{\rho}{\mu_T})(1 - s)$$

where $\dot{\omega}_o$ is the angular velocity at zero slip.

The tractive efficiency of the wheel is:

$$\eta_{tr} = \frac{Pv}{T\omega} = \frac{\mu}{\mu_T}\,(1 - s) = (1 - \frac{\rho}{\mu_T})(1 - s) = \frac{\pi}{\mu_T}\,.$$

It is the ratio of the power developed by forward motion and horizontal pull to the power input by torque and rotational velocity.

3. REVIEW OF LITERATURE

3.1 Soil Dynamics.

Soil is the most important factor in the performance of the traction wheel. Bearing capacity and traction capacity are both a function of the shear strength of a soil. For example, if the soil becomes more dense under load and gains strength, the narrow wheel will be better. If the soil does not gain strength, wider wheels may be better if all other test conditions remain the same (8). Thus the property of the soil (shear strength) is important for wheel performance.

Janosi and Hanamoto (15) cited Micklethwaite (1944) as the first to attempt to relate soil shearing strength as used in soil mechanics to determine the available thrust for a given soil and called the attention of atuomotive engineers to Terzaghi's "Stability problem" [If along a potential slip surface in the soil the shear stress from gravity or any other source (such as a moving tractor wheel, weight of tractor or an earth quake) exceeds the strength of the soil along the surface, a shear rupture and movement can occur (19)].

Starting with Coulomb's well known equation:

$$S_{max} = c + p \tan \phi$$

where,

S_{max} = Maximum shear stress in the soil $(lb/in.^2)$

c = Cohesion $(lb/in.^2)$

p = Pressure normal to the shear plane $(lb/in.^2)$

ϕ = Angle of shear resistance or the angle of internal friction,

Micklethwaite multiplied both sides by the ground contact area of

the vehicle.

$$Hmax = Smax\ A = cA + pA \tan \phi$$

where,

Hmax = Maximum traction, tractive effort, thrust, the

gross effort developed by the vehicle (lb).

For uniform normal pressure distribution the relationship between weight and pressure is:

$$W = pA.$$

Thus Micklethwaite's equation took the following form:

$$Hmax = cA + W \tan \phi.$$

The equation predicts maximum thrust based on maximum soil strength but does not consider relative displacements. For this reason Bekker (1) suggested that the shape of the soil shear stress-strain curve is similar to the displacement-natural frequency diagram of an aperiodic damped vibration. The equation which includes pressure and geometric solutions is too long and complicated to be given here.

Janosi and Hanamoto (15) suggested a simpler equation to describe soil shear stress-strain curves as:

$$S = (c + p \tan \phi)(1 - e^{-j/k})$$

where,

j = Soil deformation in the horizontal direction, in..

k = Deformation modulus of a soil shear stress-strain

curve, in..

The total tractive effort exhibited by a track or a wheel is obtained by integrating the shear stress along the ground contact area. Thus by assuming length 1 and contact width b:

$$P = 2b\int_{o}^{1}(c + p \tan \phi) \, (1 - e^{-j/k}) dx$$

The integration yields:

$$P = 2b[c + p \tan \phi] \, [1 + \frac{k}{i_o} (e^{-i_o/k}-1)].$$

For very large deformations the equation approaches Coulomb's formula.

$$(S \rightarrow \dot{c} + p \tan \phi) \text{ as } j \rightarrow \infty$$

Analytically, the drawbar pull is determined by the algebraic summation of the thrust a vehicle can develop in a given soil and resistance to motion. This relation in equation form by M.G. Bekker cited by Harrison (13) is as follows:

$$DP = H - Rm$$

where Rm is the rolling resistance and DP is the drawbar pull.

M.G. Bekker (1) developed a theory of Land Locomotion which can be obtained by describing the physical characteristics of any given soil in terms of 7 constants which are:

Strength: c and ϕ

Sinkage: k_c, k_ϕ and n

Slippage: K_1 and K_2

These values have been established arbitrarily but are a logical development of a "strength-modulus of elasticity" value system.

Harrison (13) stated that by utilizing the Bekker soil value system (1) the vehicle performance in deformable soil can be predicted accurately within $\pm 10\%$.

Harrison and Cessford (12) suggested that if the plastic parameters of the soils are known then the performance can be predicted by the

relation

$$P = (R + 0.6a + \frac{0.06\ aM}{Pl} (0.6C + 8))x$$

where P is pull, a is contact area, M is moisture content (%), C is
clay content, Pl is lower plastic limit, R is dynamic soil reaction and
x is a slip function. This relation, however, has not been proved
experimentally.

Freitag et al (7) stated that the principal factors that are
important in the behaviour of soil-machine systems involve forces or
displacements. Therefore, only the soil characteristics that have a
fairly direct bearing on forces or displacements should be considered.
On this basis Freitag did not consider such soil quantities as water
content, Atterberg limits and mineral types.

Soil strength has a drastic effect on rolling resistance (30). This
was studied by Wismer (35) who concluded that soil strength between the
soil surface and the remainder of the soil mass at the time of the test
can drastically affect powered wheel performance. Wismer also suggested
that this may not have very much effect on towed wheel performance.

There is a critical need for a method by which a reasonably
accurate assessment of soil strength can be made rapidly without the use
of special instruments and by personnel without special training. The
aim is to predict traction performance of the soil based on soil
strength.

For predicting soil trafficability, researchers have used various
kinds of instruments. Pavlics (23) developed a wheeled type soil
measuring instrument for quick and continuous soil strength measurement.
Results were in agreement with Bevameter tests. The Bevameter (Bekker

value meter) is a device designed and originally built by the Land

Locomotion Laboratory, United States Army to measure the physical soil

values (k_c, k_ϕ, n, c, ϕ) proposed by Bekker, utilizing sinkage plates

and a shear annulus.

Numerous researchers have worked on and evaluated the performance

of penetrometers for soil trafficability. McKibben and Hull (21) used

Iowa and Rototiller penetrometers for evaluating wheel performance on

deformable soils. The correlation between the rolling resistance

measurements and penetrometer readings was between 0.92 to 0.98 in all

the cases. Hendrick (14) found a strong correlation between penetrometer

readings and root penetration and elongation, off the road vehicle

trafficability, soil hydraulic conductivity, soil parameters and also

soil strength profile. Shuman et al (27), Knight and Rula (18),Hammitt

(11),Sloss (28) and Hendrick (14) all worked and used penetrometers

developed by the Waterways Experiment Station (WES). All found the

penetrometer to be a good instrument for soil trafficability prediction

research. Trafficability is measured empirically in terms of cone

index. Cone index is the force per unit base area required to penetrate

a soil (normal to the surface) with a 30-degree right circular cone.

Freitag et al (7) suggested the problem of identifying and

measuring soil properties must be resolved to analyse the basic

interactions of soil-machine systems. Many soil properties have been

listed and many devices have been created to measure these properties,

but little evidence exists concerning their validity and applicability.

The Sheargraph, Bevameter, direct shear machine and shear vane, etc.

have been used for trafficability studies (7). Many soils whose strength

are low in situ will become even weaker under the action, or remoulding

effect of a vehicle. To estimate the cone index that will prevail

under the moving vehicle, a remoulding test is necessary (18). In the

various studies involving soil-machine interaction, a number of different

soil properties have been mentioned, or their existence at least

hypothesized. This listing is given in Appendix 1. The devices used

for measurement of soil properties are given in Appendix 2.

3.2   Wheel Geometry.

Generally the traction capacity of the tractor depends (apart from

its dimensions) on the tires, the traction capacity of which is

characterized by the relationship between the slip of the tire, and its

traction coefficient. Traction is influenced by the tread or make of

the tire, axle weight, tire size and inflation pressure.

The selection of the proper tire size, shape and construction for

a given agricultural operation must remain far more an art than a

science until a proven parametric description of the tire soil system is

available (32).

Geometric factors which influence the wheel performance are:

Tire diameter	Lug shape	Inflation pressure
Tire width	Lug height	Tire deflection
Number of tires	Lug angle	Rim width.
Tire spacing	Lug spacing	Rim diameter
Tire shape	Traction aids	Carcass construction
	Tread material	Carcass stiffness.

It is well known (8) that the relative rigidity of a tire has an

influence on the performance of the wheel. In many studies this relative

rigidity has been evaluated in terms of the inflation pressure.
Inflation pressure may be a good measure of rigidity for tests with a
particular tire, but the same inflation pressure will have a different
meaning with a tire of different size and stiffness. Investigators (8)
have considered the deflection of the tire to be a more generally useful
measure of tire rigidity.

A number of researchers have worked on the geometric factors which
effect wheel performance. Wismer (35) studied the effect of load, tire
deflection and soil strength on the pneumatic wheel and arrived at the
conclusion that on soft soil, deflection has little influence, but in
firm soil, the greatest deflection produces the greatest pull at 20%
slip. Since the combination of firm soil and high deflection resulted
in a relatively large contact area, the result indicated that a large
contact area enhances performance.

Sauve (25) stated that lowering the inflation pressure (on loose
soils) increased traction area and decreased the rolling resistance.

Kliefoth (17) studied the effect of wheel tread, diameter, width
and inflation pressure on the traction coefficient for different soils.
A tire with open center lugs did not have much influence on
trafficability. According to Kliefoth the traction coefficient increases
with an increase in tire diameter, but since the increase is not directly
proportional to the diameter, the relationship between them then
must be determined.

Taylor et al (31) studied the effect of diameter on performance
of powered wheels and found that at the same normal load and inflation
pressure, increased diameter increased both pull and coefficient of
traction.

Vandenberg and Reed (33) stated that, except for maximum traction,

removal of lugs caused nearly twice as much improvement in traction as radial ply construction.

Summarizing all the reported results on the performance of tire parameters on traction it may be stated that if pneumatic tires are evaluated with tire deflection constant, the pull that the tire can develop decreases as load is increased. Also, at constant tire deflection and load, pull increases approximately in proportion to increases in tire width (8). Pull increases with increasing tire diameter, but since the increase is not directly proportional to the diameter, it is necessary to determine this relationship (17). Tread pattern, lug size and shape, and traction aids were found to exert marked influence in certain soil conditions, but in others they were of little consequence (8).

3.3 Tire-Soil System.

There is a great need to study the tire-soil system to predict traction accurately for a given soil. Researchers have studied tire-soil systems in a number of ways.

Kennedy (16) developed a revised mobility index (MI) formula from the test results of self-propelled wheeled vehicles. In the original formula the effects of contact pressure, weight, tire, grouser, wheel load, clearance, engine and transmission were considered. In the revised MI formula, the factors were the same but some were adjusted. The following factors remained unchanged: grouser factor, wheel load factor, clearance factor, engine factor, and transmission factor.

Dimensional analysis is being used by many researchers to study the relationship between the soil and the wheel. The technique is based on a consideration of the dimensions of the system parameters (parameters

should be dimensionally balanced). Dimensional analysis also provides a convenient means for determining the requirements for similarity (the basis of model theory). The Pi theorem is used in most of the studies of soil-wheel relations.

Freitag (9) cited the work of Roma and McGowan on beach sand. The Pi terms W/CL^2, T, S, δ/d and b/d were considered. It was found that wide tires tend to perform better than narrow tires for the same value of principal Pi terms.

Vincent et al (34) at the University of Michigan studied the Pi terms V^2/gL, $W/\gamma L^3$ and b/d. Functional relation between dependent and independent parameters could be expressed in the form

$$\frac{P_T}{W} = f\left(\frac{W}{\gamma d^3}\right) + g\left(\frac{b}{d}\right) + P\left(\frac{V^2}{gd}\right)$$

Results indicate that P_T/W ratio decreased slightly with an increase in the b/d ratio, and increased slightly when the velocity Pi term increased.

Freitag (9) used dimensional analysis for the tire-soil system in the study on soft soils. To be completely valid and useful, a dimensional analysis of a system must include all of the parameters that have an influence on the behaviour of the system. The independent parameters that were considered in the analysis are listed in table 1.

The four dependent parameters, pull (P), towed force (rolling resistance) (P_T), torque (T) and sinkage (Z) were considered for the study of the tire-soil system. The force P_T represents the force required to tow the freely rolling tire. P_T occurs when the torque is zero, but the slip has some negative value that depends upon the independent tire and soil parameters. The other dependent parameters measurements were

TABLE 1: INDEPENDENT TIRE-SOIL SYSTEM PARAMETERS.

Parameter	Symbol	MLT Units
Soil:		
Friction angle	ϕ	--
Cohesion	c	$ML^{-1}T^{-2}$
Specific weight	γ	$ML^{-2}T^{-2}$
Spissitude	β	$ML^{-1}T^{-1}$
Tire:		
Diameter	d	L
Section width	b	L
Section height	h	L
Deflection	δ	L
System:		
Load	W	MLT^{-2}
Translation velocity	V	LT^{-1}
Slip	s	--
Tire-soil friction	μ_1	--
Acceleration due to gravity	g	LT^{-2}

made at the 20 percent slip point ,where the pull developed by the tire
usually was very near the maximum that could be developed. Sample
pull-slip and torque-slip curves for clay are given in figure 2.

The following 14 Pi terms were developed

$$\pi_1 = P/W \qquad\qquad\qquad \pi_3 = T/dW$$

$$\pi_2 = P_T/W \qquad\qquad\qquad \pi_4 = Z/d$$

$$\pi_5 = \mu_1 \qquad\qquad\qquad\qquad \pi_8 = b/d$$

$$\pi_6 = \phi \qquad\qquad\qquad\qquad \pi_9 = h/d$$

$$\pi_7 = s \qquad\qquad\qquad\qquad \pi_{10} = \delta/h$$

$$\pi_{11} = Cd^2/W \qquad\qquad\qquad \pi_{13} = dV\beta/W$$

$$\pi_{12} = \gamma d^3/W \qquad\qquad\qquad \pi_{14} = gd/V^2.$$

The cone index C provides an adequate measure of the soil properties.
In clay, the average cone index was interpreted to be equivalent to
cohesion c. In sand, the cone index gradient G was considered to be
affected principally by the density of the soil. Thus, in sand, the
only Pi term influenced by the soil parameter was $\gamma d^3/W$; and in clay, only
the terms Cd^2/W and $\beta Vd/W$ contained soil parameters. Pi terms, b/d and
δ/h were used as the principal independent tire variables. Under controlled
test conditions and using simplifying assumptions, the relationship
between the independent and dependent Pi terms were as follows.

In clay

$$P_T/W, \ P/W, \ Z/d, \ T/dW = f(\ Cd^2/W, \ b/d, \ \delta/h).$$

and in sand

$$P_T/W, \ P/W, \ Z/d, \ T/dW = f(Gd^3/W, \ b/d, \ \delta/h).$$

Freitag has consolidated the independent parameters of soil-tire
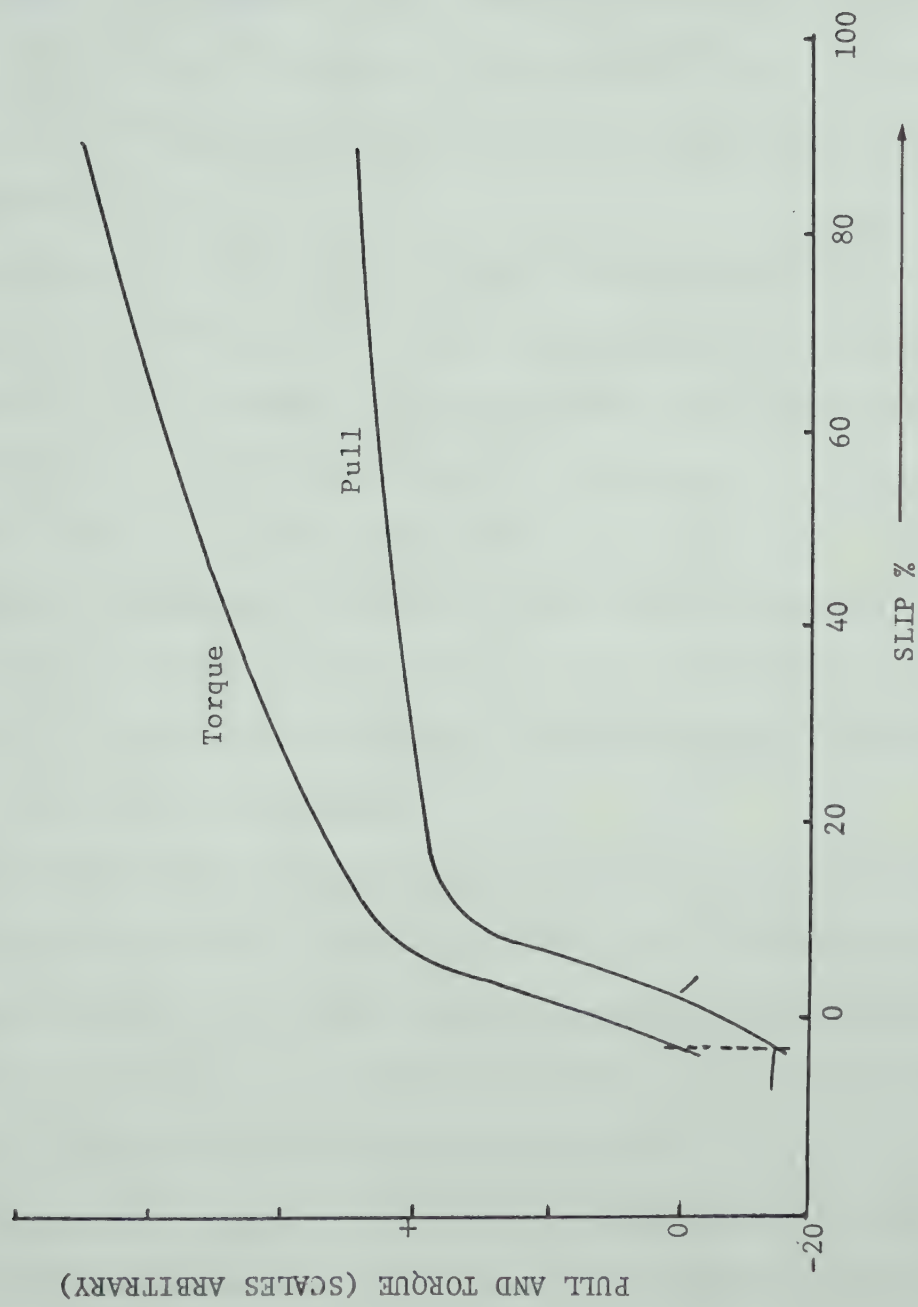system at 20% slip value to a single dimensionless prediction term for

Figure 2: Sample pull-slip and torque-slip curves.

clay ($Cbd/W.(\delta/h)^{1/2}$) and for sand ($G(bd)^{3/2}/W.\delta/h$) for circular cross

section tires. Tire performance is described by towed force/load,

pull/load, sinkage/tire diameter, and torque/load x active tire radius.

Turnage (32) suggested on the basis of subsequent analysis' that

$Cbd/W.(\delta/h)^{1/2}$ should be altered to $Cbd/W.(\delta/h)^{1/2} 1/(1 + b/2d)$ to

predict the performance coefficient for both circular and rectangular

cross section tires.

Looking at the effect of tire size and deflection on the wheel

pull, values of $Cbd/W.(\delta/h)^{1/2} 1/(1 + b/2d)$ are more influenced by changes

in diameter than by changes in width because of the factor $1/(1 + b/2d)$

(32). This is illustrated in Appendix 4, where $bd.1/(1 + b/2d) =$

$2bd^2/(2d + b) = K$ for initial values of d = 1.0 and b = 1.0. Changes in

deflection (δ) influence the value of the prediction term in a similar

manner as b or d but δ is less pronounced than b or d. For off-road

operations, a tire should be designed for and operated at the largest

value of deflection practicable.

Rymiszewski (24) developed computer techniques for determining

families of "equivalent" tires which produce the same DP/W in the

homogeneous medium. This study will aid wheeled vehicle designers in

selecting proper wheel forms for use in new vehicle configuration

requiring optimum off-the-road soft soil mobility.

The tire-soil system for all types of soils should be studied to

predict traction performance. At present tire sizes are selected by

criteria that give the maximum loads permissible for acceptable tire

life, rather than on the ability of the tire to perform useful work on

soft soils. A parametric equation should be developed so that tires

can be designed to obtain acceptable traction, and tractors can be

designed for tires.

4. EQUIPMENT

4.1 Equipment Used for Tire-Soil System.

For this study, (a) torque, (b) pull, (c) weight transfer, (d)
rear wheel speed and (e) actual forward speed were measured with the
following equipment.

1. Test tractor: Massey-Ferguson 135 Diesel model, multi-power
    having 6.00-16 front tires and 14.9-24 rear tires (figure 3).
    A special frame supported by the three point hitch was installed
    for additional rear wheel weight. A complete description of the
    test tractor is given in Appendix 5.

2. Loading unit: A load car and a Massey-Harris 44 tractor were
    used to provide drawbar load for the test tractor. The load car
    consisted of two Massey-Harris 55 rear ends and gear boxes
    coupled to two "Hydreco" hydraulic pumps (62 gallons/min. at 1800
    rpm) as shown in figure 4. The load tractor was used on loose soil
    for higher gears.

3. Torque transducer: A torque transducer built by Berlage (2) was
    installed in the left rear wheel. The torque was measured as a
    force in a compression cylinder. The four 120 ohm SR-4 strain
    gauges were in a Poisson arrangement. The five wire shielded
    cable from the torque transducer and the other signal cables were
    connected to a 24 pin-female connector (figure 5).

4. Pull transducer: A 0-type transducer, (diameter 4 inches and cross
    section 9/16 x 9/16 inches) with four 120 ohm EA-06-250BG-120
    strain gauges, (two in tension and two in compression) in a
    Wheatstone bridge arrangement was installed between the test tractor
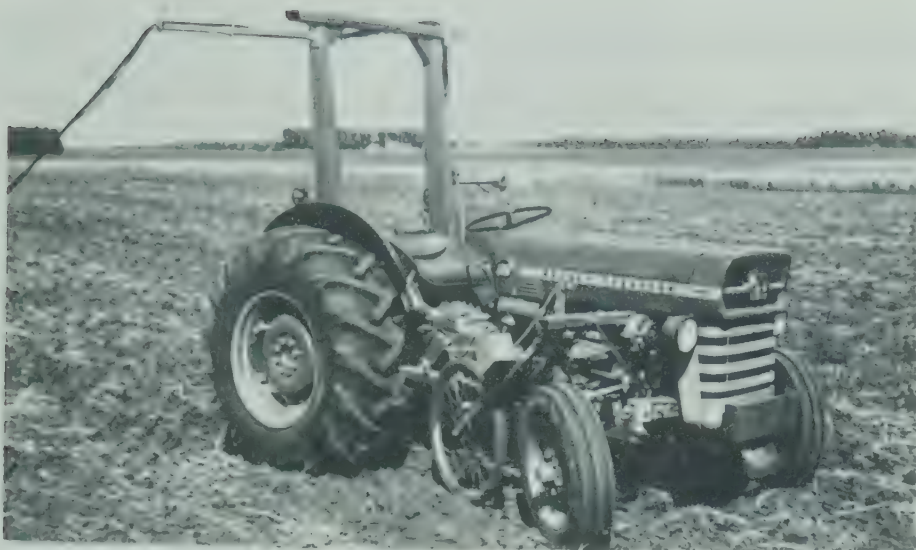
Figure 3: Massey-Ferguson 135 test tractor with forward speed indicator.

Figure 4: Test tractor and load car.

drawbar and the load car.

5.   Weight transfer: Four 120 ohm EA-06-250BG-120 strain gauges
     (two in tension and two in compression) were placed on the front
     axle of the test tractor.

6.   Rear wheel speed indicator: A D.C. generator was driven from the
     left rear wheel by a chain drive arrangement through a 1:10 gear
     box (figure 5).

7.   Forward speed indicator: A 24 inch pneumatic bicycle wheel was
     used as a fifth wheel for actual forward speed indication.   A D.C.
     generator was connected to the output shaft of a 1:27 gear box.
     The input shaft of the gear box was driven by a sprocket and chain
     arrangement.   The frame with the bicycle wheel and the generator
     assembly was attached to the right side of the tractor as shown
     in figure 3.

8.   Recording equipment: A 12-channel ultraviolet SE 2005 type recorder
     (figure 6) was used to record the outputs on direct print-out
     paper (Kodak Linagraph Direct Print Paper, 6 in. x 100 ft, Spec.
     2).   Five plug-in pencil-type recording galvanometers, B.100
     (sensitivity 0.0025 ma/cm and damping resistance 250 ohms) were used.
     Signals from the Wheatstone bridge circuits were taken through
     three Honeywell Accudata 104 D.C. amplifiers and 105 Gauge control
     units (0 to 250 times amplification and response $\pm$ 1% dc to 20 kc)
     to the ultraviolet recorder.   Signal conditioners with bridge balance
     and calibration circuitry to control gauge excitation and balance
     (frequency response dc to 10 kc) and calibration resistances of
     20K were used.
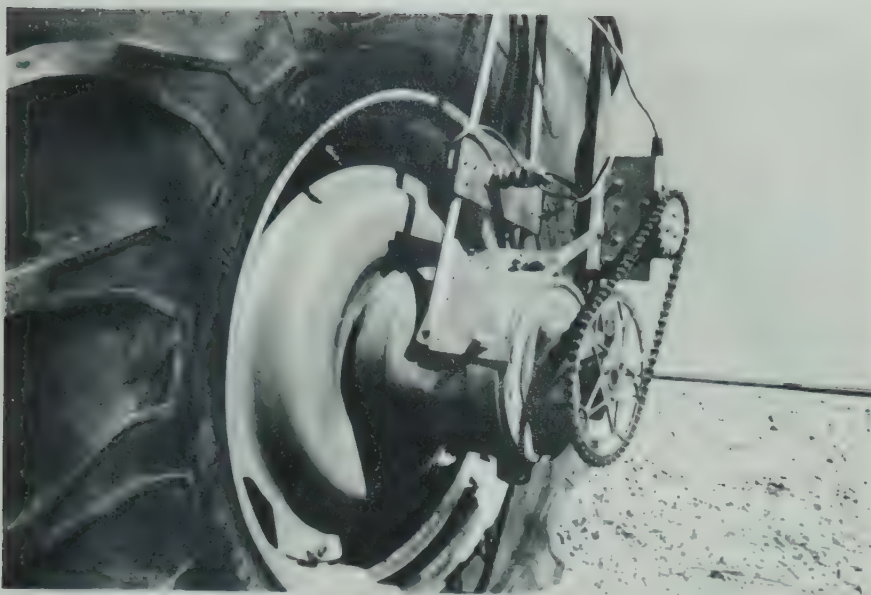
Figure 5: Torque transducer and rear wheel speed indicator.
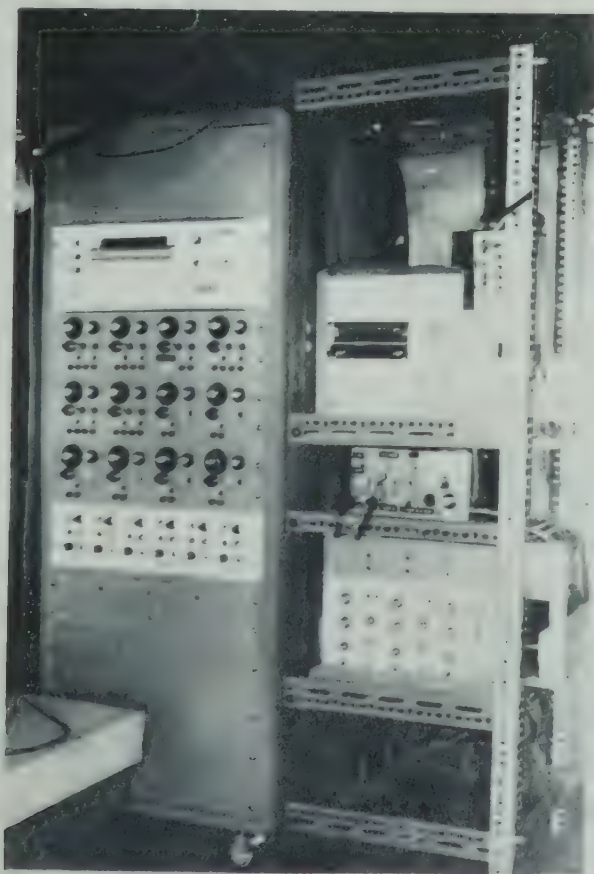
Figure 6: Recording equipment;
U.V. recorder,
amplifiers and gauge
control units.

9. Portable power source: Kohler electric plant, Model 1.25 mm 25, serial 326286, 180 rpm, 1250 watts, 120 volts and 60 cycles per second.

The equipment described in 8 and 9 above was installed on the mobile van and the remainder on the test tractor. A set of four 50 foot shielded cables were used to connect the 24-pin connecter to the recording unit inside the van.

4.2 Equipment Used to Measure Soil Physical Parameters.

1. Soil penetrometer: A hand operated, 30° circular stainless steel soil cone penetrometer (A.S.A.E. Recommendation: ASAE R313.1)(36) was used for measurement of soil penetration resistance. The cone base was 0.505 inches in diameter (area of 0.2 square inches) and the shaft was graduated at 2 inch intervals (figure 7).

2. Soil sampler: A steel tube three feet in length with an inside diameter 3/4 inch and outside diameter 15/16 inch having a core length of 15 inches was used for taking soil samples. The soil sampler was manufactured by Soiltest Inc. Evanston, Ill., U.S.A.

3. Cohron sheargraph: Manufactured by Soiltest Inc., Evanston, Ill., U.S.A. A hand operated coiled spring torque and load measuring sheargraph (figure 7) with a circular head of 2 in.^{2} was used to measure the shear strength of the field soil in situ near the surface (1 cm depth or less).

4. Neutron density/moisture surface gauge and gauge scaler: For quick, non-destructive and instant measurement of density (60-160 lb/ cu ft) and moisture (1 - 32 lb/cu ft) a surface gauge (figure
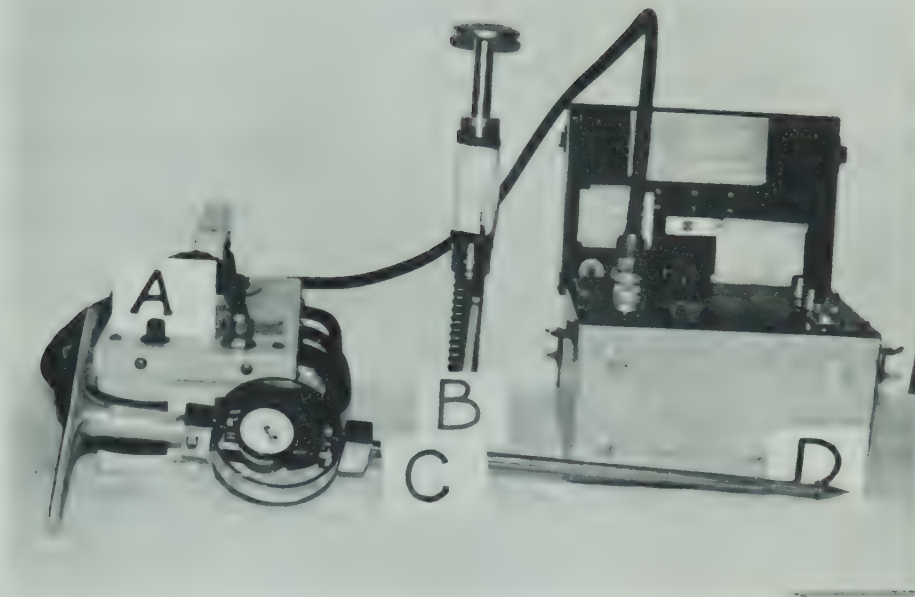
Figure 7: Equipment for measuring soil physical parameters,
    A. Neutron Density/moisture surface gauge.
    B. Cohron Sheargraph.
    C. Soil Penetrometer.
    D. Gauge Scaler for Neutron Density/moisture surface gauge.

7), manufactured by Nuclear-Chicago, with operating voltage 1300-1450 volts was used. A gauge scaler with count capacity 0 to 99,999 counts and time duration 0.25 to 2 minutes was used for counting the number of pulses detected by the gamma ray and neutron detector in the surface gauge. The gauge utilizes a neutron source (4 mc. Radium-beryllium) which emits both gamma (for density measurement) and neutron (for measuring moisture content) radiation.

4.3 Calibration.

To get constant output from day to day for a given input, the calibration circuitry of the Accudata 105 Gauge Control Unit was used. A simulated strain of 20 lines of deflection with a 20K resistor was obtained by adjustment of the amplification control.

1. Torque transducer: A special frame with a lever arm of 6.1 feet in length was attached to the disc of the rear wheel of the test tractor for static torque calibration (figure 8). Calibration was done by raising the left rear wheel, locking the brakes and the differential and adding the weights on one end of the lever arm (up to 4000 lb ft). One weight was 500 lb ft. Non linearity of the calibration curve (figure 10) at low torque values was probably not due to friction but due to inherent characteristics. Calibration was done in the same direction as the torque was applied in the field to eliminate the effect of rotational direction.

2. Weight transfer: Two platform scales were placed under the front wheels (figure 9). The rear wheels were raised to the same height as the front wheels. A hydraulic jack was placed under the front

Figure 8: Torque transducer calibration.

Figure 9: Weight transfer calibration.
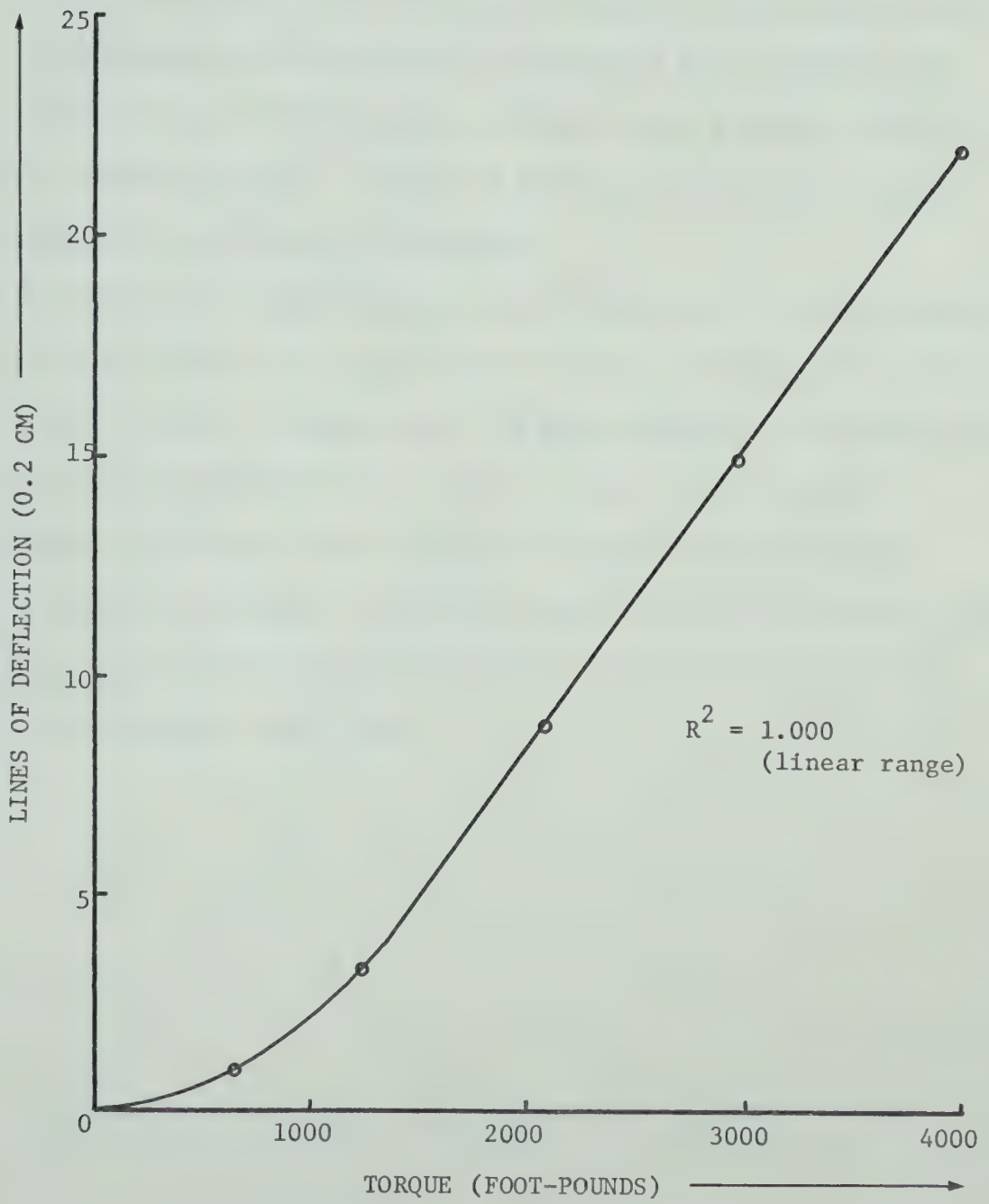
Figure 10: Calibration of the torque transducer.

axle. Lines of deflection versus weight transfer up to 1530 lb
(weight on the front wheels) were plotted as shown in figure 11.
A straight line relationship was obtained.

3.   Pull transducer: At the Strength of Materials Laboratory in the
Civil Engineering Department, the ring type pull transducer was
calibrated up to 5000 lb with a Baldwin Testing Machine (200,000
lb maximum capacity). Figure 12 shows the relationship between
pull in lb and lines of deflection.

4.   Rear wheel and actual forward speed indicators: The test tractor
was towed behind an International Harvester Company (I.H.C.) 756
diesel tractor. Distance and time were measured to calculate the
speeds for both the forward and rear wheel speed indicator. A
sample calibration curve is given in figure 13. By assuming
there was no slippage of the rear wheel in the towed position, the
zero slip condition was established. Lines of deflection were
plotted against speed (mph).
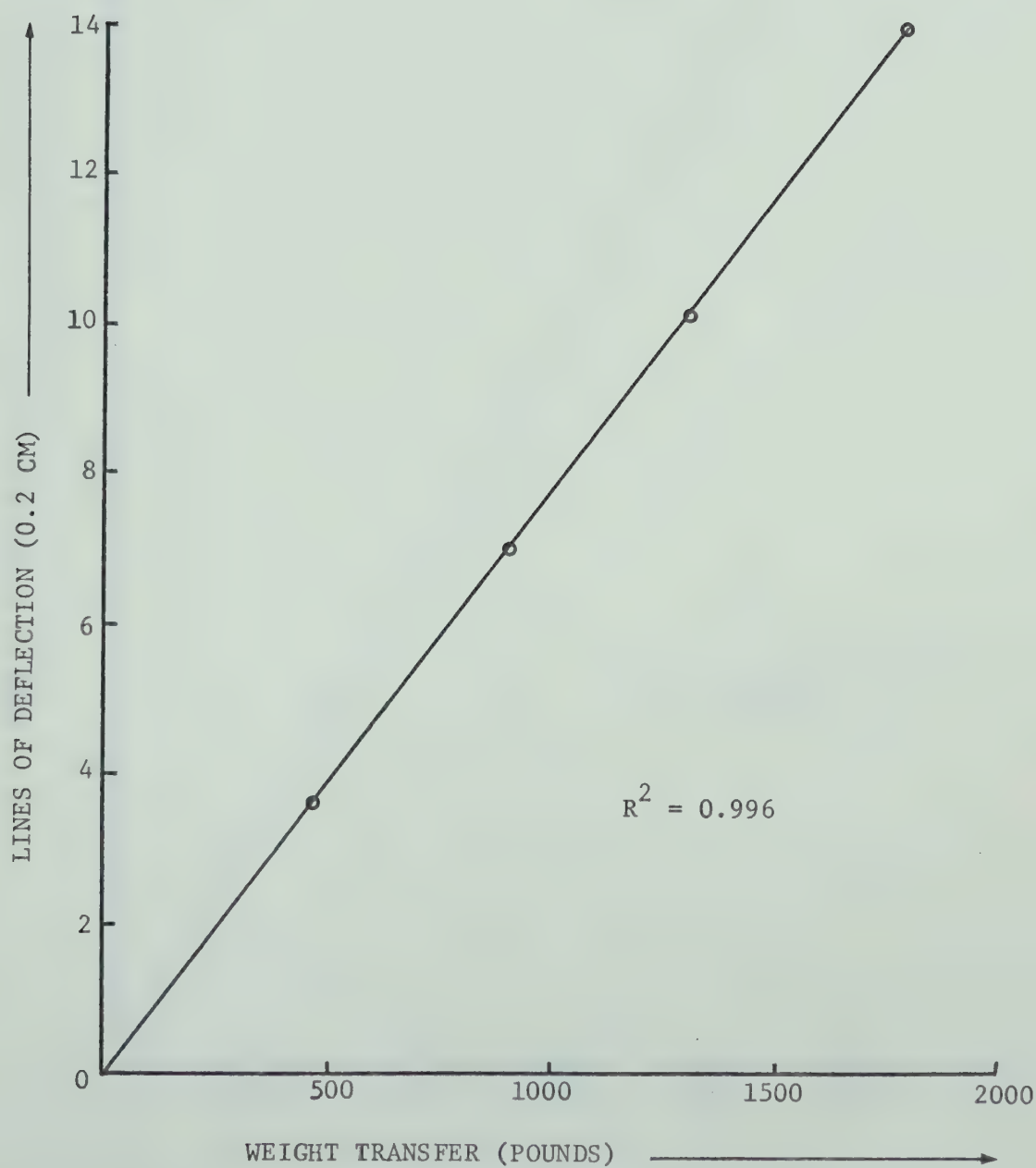
Figure 11: Calibration curve for weight transfer.
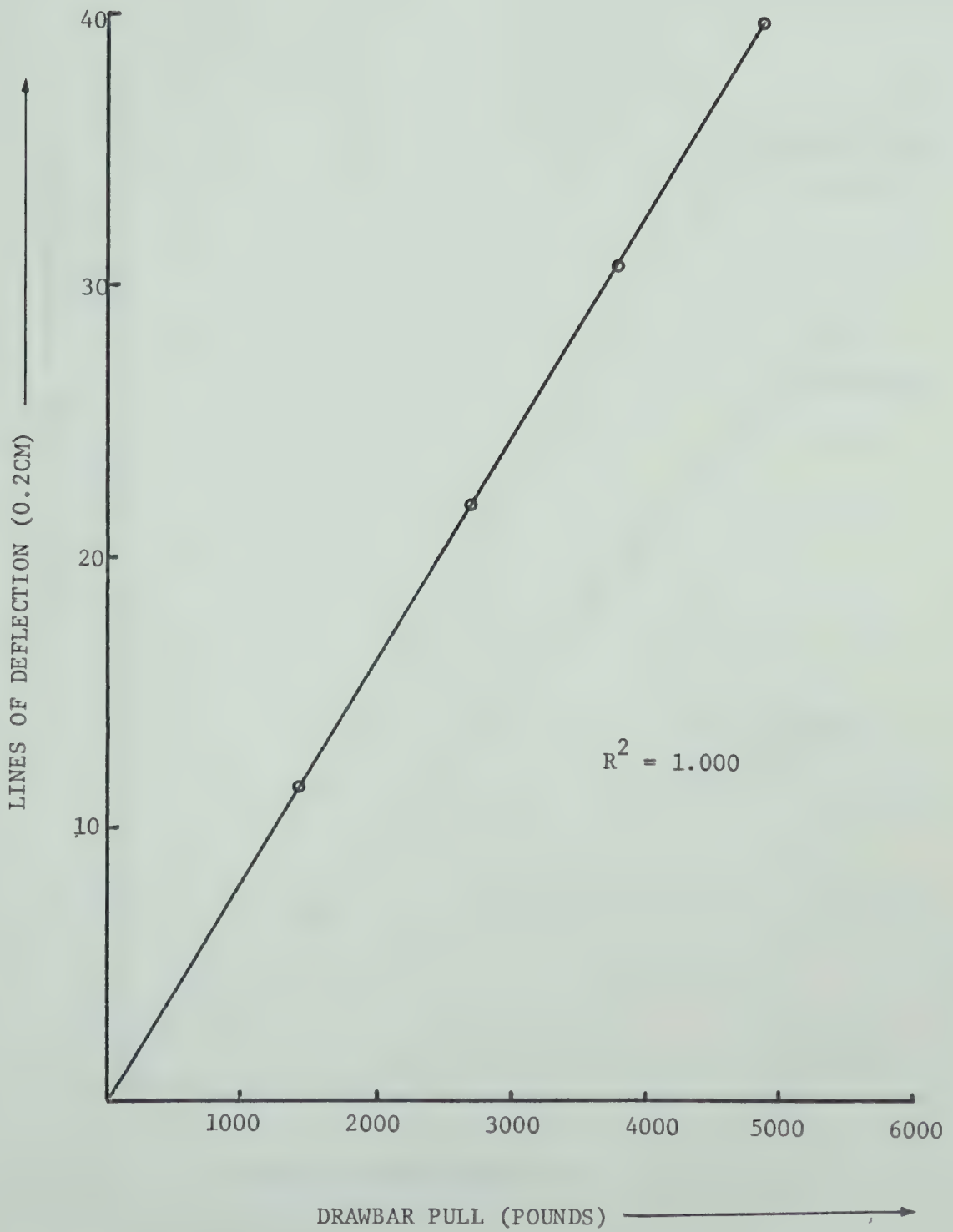
Figure 12:   Calibration for the pull transducer.
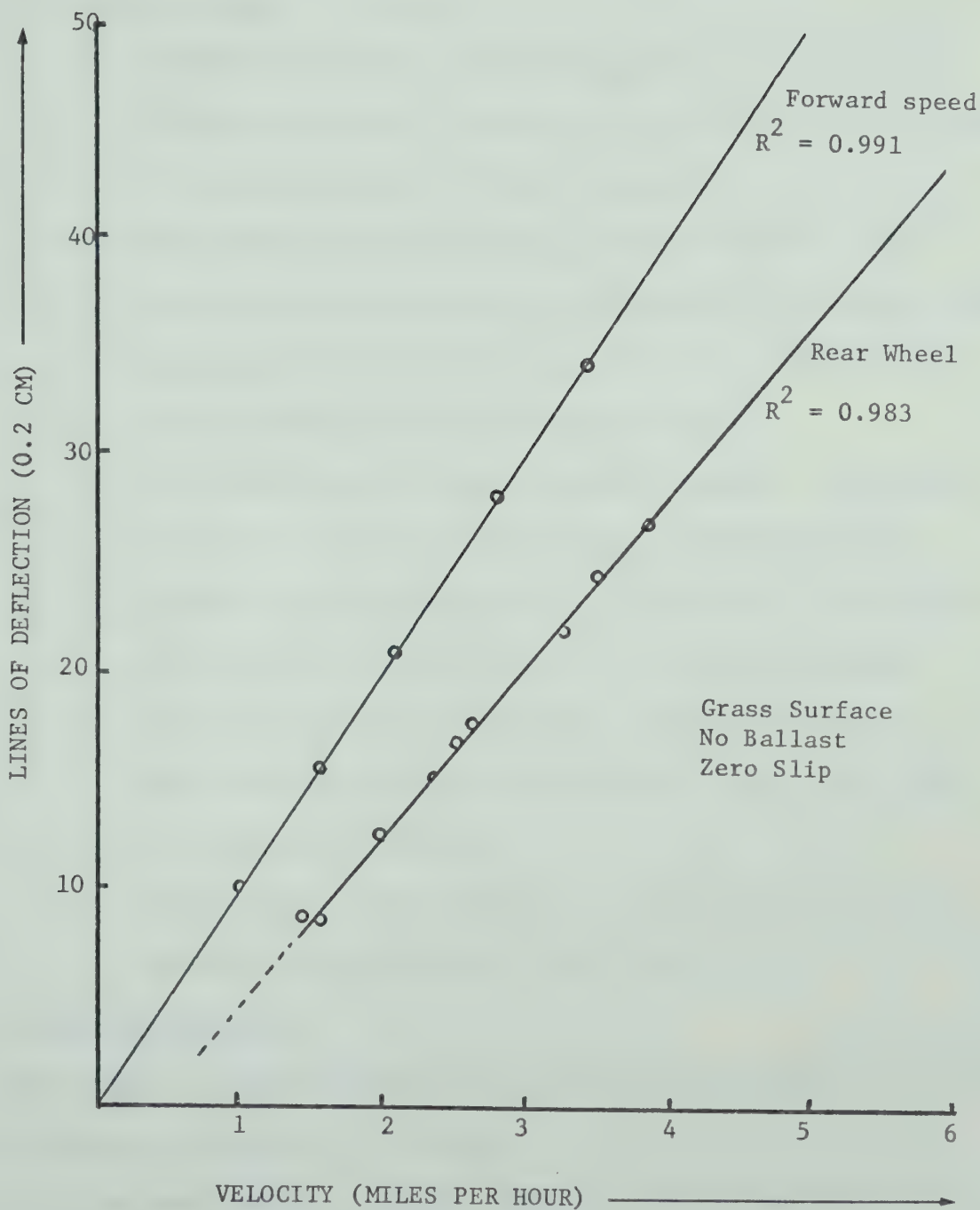
Figure 13: Calibration of speed transducer.

5. TESTING PROCEDURE

5.1 Preliminary Test.

Preliminary testing of recording equipment and transducers resulted in some changes. These were:

1. A change in position of strain gauges from the outer end of the front axle to the inner side, to get more deflection for the same amount of weight transfer.

2. The galvanometers initially used were replaced by more sensitive galvanometers with a sensitivity of 0.0025 ma/cm as compared to 0.13 ma/cm to obtain an increase in lines of deflection for the same input voltage.

3. By installing the torque transducer assembly the position of the left rear wheel was changed. To obtain equal distance of the rear wheels from the center, the position of the right rear wheel disc in the rim was changed.

4. The zero position of the weight transfer recording was done while the driver was on the test tractor seat and the tractor stationary.

5. The electrical noise picked up by the D.C. generator assemblies was eliminated with filters.

5.2 Field Test Procedure.

Tests with the Massey Ferguson 135 tractor on three different surface conditions were carried out as follows:

1. The test tractor, portable generator and loading units were serviced for fuel and oil.

2. The portable generator was started, the recording equipment and amplifiers turned on approximately an hour before the

actual start of the test run.

3.   The required weight and pressure for the front and rear tires of the test tractor was obtained.

4.   The test tractor and load car were positioned with the van on their right. The 50 ft cable with the 24 pin connector was connected to the recording equipment. Outputs from the transducers were balanced, calibrated, and positioned at the proper place on the recording paper.

5.   The rolling radius was determined by measuring the distance travelled by ten wheel revolutions.

6.   The paper speed of 2.5 mm/sec. and time line interval of 0.5 second was selected and used for all runs.

7.   For all runs, the test tractor was driven at approximately 2000 engine rpm. Rated speed (mph) at 2000 rpm for all gears is given in Appendix 5. The drawbar load was applied gradually by (a) regulating two hydraulic valves when the load car was used as a loading unit, and (b) decreasing the forward speed and brakes if necessary when the Massey Harris 44 tractor was used as the loading unit. The load applied during each 100 feet of run resulted in slip values up to approximately 80%.

8.   Tests were run on each surface with every set of ballast; all four gears were repeated three times.

9.   After visual inspection the recording charts were protected from sunlight by putting the paper rolls in a light proof box.

10. To eliminate bias in collecting soil data, a one foot square
     ring was randomly thrown at five different places in the
     test area and soil samples, density and penetration readings
     were taken. Soil samples for moisture percentage and
     penetration readings were taken at two, four and six inch
     depths. Penetration readings were repeated five times at each
     location. Two density readings were taken at each location.
     The gauge was turned 90° for the second reading.

11. Soil shear strength readings were taken with the Cohron
     sheargraph.

5.3 Experimental Design.

The experiment was designed to characterize the soil conditions by
the traction performance parameter,coefficient of traction. The effects
of ballast and speed on the coefficient of traction for the three
surface conditions; grass, fallow and stubble were studied.

Nine hundred and thirty pounds of calcium chloride solution was
added to the rear wheels of the test tractor as liquid ballast. The
weight on the rear wheels was varied from 3470 lb to 5290 lb. For this
study four levels of ballast; 0, 2,4 and 5 were added (pressure was
constant at 14 psi). One level of ballast (364 lb of weight on the rear
axle) consisted of three cast iron weights of 94 lb each added to the
special frame on the rear end of the tractor and one 82 lb cast iron
weight added to the front so that the static weight on front axle
remained constant. The test was carried out on three surface conditions
of Malmo silty-clay loam.

With each surface and ballast combination, four gears were repeated

three times in the tests. Twenty data points from each test run were taken from the U-V recorder chart.

The effect of gears and repeats was expected to be less than the effect of ballast and surface conditions. It was also not practically possible to randomize the ballast and surfaces as this would require large experimental units, hence these are made the "whole units" and further divided into "sub units" of gears and repeats. The performance parameter, coefficient of traction (μ), was studied because traction capacity is characterized by the relationship between slip of the tire and its traction coefficient (17). This relationship can be utilized to predict the drawbar pull capability of a tractor in the field and the ballast needed to supply sufficient drawbar pull (4). A split-plot experimental design was therefore used to determine the effect of surface conditions, ballasts and gears (speed) on the coefficient of traction (μ).

6. ANALYSIS OF DATA, RESULTS AND DISCUSSION

6.1 Analysis of Data.

The direct recording chart papers were analyzed as follows:

1.   The towed test tractor charts were analyzed for (a) rear wheel

speed, (b) rolling resistance and (c) actual forward speed.

2.   From zero slip to approximately 80% slip, 20 points were read

for torque, pull, weight transfer, rear wheel speed and actual

forward speed. Torque was in the linear range (figure 10).

3.   The lines of deflections for all test run data were punched on

computer cards and analyzed with a Fortran IV program, written

by the author.

4.   Values of soil physical parameters of the three surfaces are

given in Appendix 6. Dry and bulk density and moisture content

were calculated from moisture/density surface gauge readings.

Moisture content was also obtained by the gravimetric method.

Values of c and ϕ were obtained from the sheargraph chart paper.

Cone index was calculated by dividing penetration readings (force

lb) by the base area of the cone.

6.2 Experimental Error Analysis.

An analysis of experimental error in a representative set of data

showed the maximum error to be below 3%.

6.3 Presentation of Data.

The tests were carried out on three soil surfaces at the University

of Alberta, Agricultural Engineering Farm (Ellerslie). The surface

conditions were: grass land, summer fallow and stubble. Mechanical

analysis of the soil is given in Appendix 7 and classification of the

soil is given in Appendix 8.

6.3.1 Clay Mobility Number.

One part of the study was to investigate whether the clay mobility number developed by the U.S. Army Engineer Waterways Experiment Station (WES) for both circular and rectangular-section tires in clay soil could be used to predict the performance of agricultural tires in an Alberta soil. In this study the clay mobility number is related to the following performance coefficients: Pull number, P_{20}/W which is the coefficient of traction at 20% slip and torque number, T_{20}/Wr_a* which is the coefficient of gross traction at 20% slip.

The clay mobility number developed by Freitag and altered by Turnage from tests with circular and rectangular-section tires is dimensionless and as previously defined in section 3.3 is:

$$\text{Clay Mobility Number (C.M.N.)} = \frac{Cbd}{W} \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + b/2d}$$

where,

d = outside diameter of the inflated, but unloaded, treadless tire.

b = maximum outside width of the cross section of the inflated, but unloaded, tire.

W = the vertical force applied to the tire through the axle.

δ = difference between the section height and the loaded section height.

h = distance from the lip of the rim flange to the periphery of the treadless tire.

C = cone index, lb/square inch. (Average 0 - 6 inches).

* Active radius $r_a = (d - \delta)/2$

Although a full range of slip values was obtained during the tests, only the data at the towed point (zero torque) and at 20 percent slip were used. Values of torque, pull and weight transfer were found at 20 percent slip from the regression equations of each dependent variable (slip was the independent variable). In all the regression equations, the squared multiple correlation coefficient was between 0.747 and 0.948.

The prediction of the performance of an agricultural tire (14.9-24) was done on three surface conditions of an Alberta soil (Malmo silty-clay loam). The results (data points in figures 14, 15 and 16) of an agricultural tire show that the previously developed clay mobility number can be used to predict pull and torque performance of an Alberta soil. The curves* developed by WES can be used for prediction of performance on an Alberta soil.

The relationship between clay mobility number and pull number, and clay mobility number and torque number for the test data were not done as the range of test data was very small. The points in figures 14, 15 and 16 are considered within reasonable accuracy of the predicted curves. The scatter of data in figure 16 was probably due to variable conditions in the test field (standard deviation of $\pm$ 17.2 lb/in.^{2} in penetration resistance). The top soil (up to 2 in.) was very loose as compared to the soil below 2 in. (2 in. to 6 in.).

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* The curve for clay mobility number and pull number is from Freitag's Report (9) for 15% deflection.

The curve for clay mobility number and torque number is from Turnage's paper (32).

The results on the grass surface are summarized in table 2.

TABLE 2: RESULTS OF TESTS ON GRASS SURFACE.

Torque on Both Wheels (lb ft)	Total Pull (lb)	Rear Wheels Weight (lb)	Pull No.	Torque No.	Clay Mobility No.
5078	1804	4036	0.45	0.67	8.47
5629	2052	4450	0.46	0.68	7.96
5722	2162	4841	0.45	0.64	7.54
6083	2393	5229	0.46	0.63	7.18
6180	2377	5581	0.43	0.60	6.90
6537	2632	6000	0.44	0.59	6.60
5490	2162	6347	0.34	0.46	5.74
6583	2587	6593	0.39	0.54	5.50
6606	2679	6988	0.38	0.51	5.14

0.8

0.6

Pull Number $\frac{P}{W}$

0.4

0.2

0

0   2   4   6   8   10   12

a)

$$C.M.N. = \frac{Cbd}{W}(\frac{\delta}{h})^{1/2} \cdot \frac{1}{1+b/2d}$$

0.8

+0.075

0.6

Torque Number $\frac{T}{Wr_a}$

0.4

0.2

0

0   2   4   6   8   10   12

$$C.M.N. = \frac{Cbd}{W}(\frac{\delta}{h})^{1/2} \cdot \frac{1}{1+b/2d}$$

b)
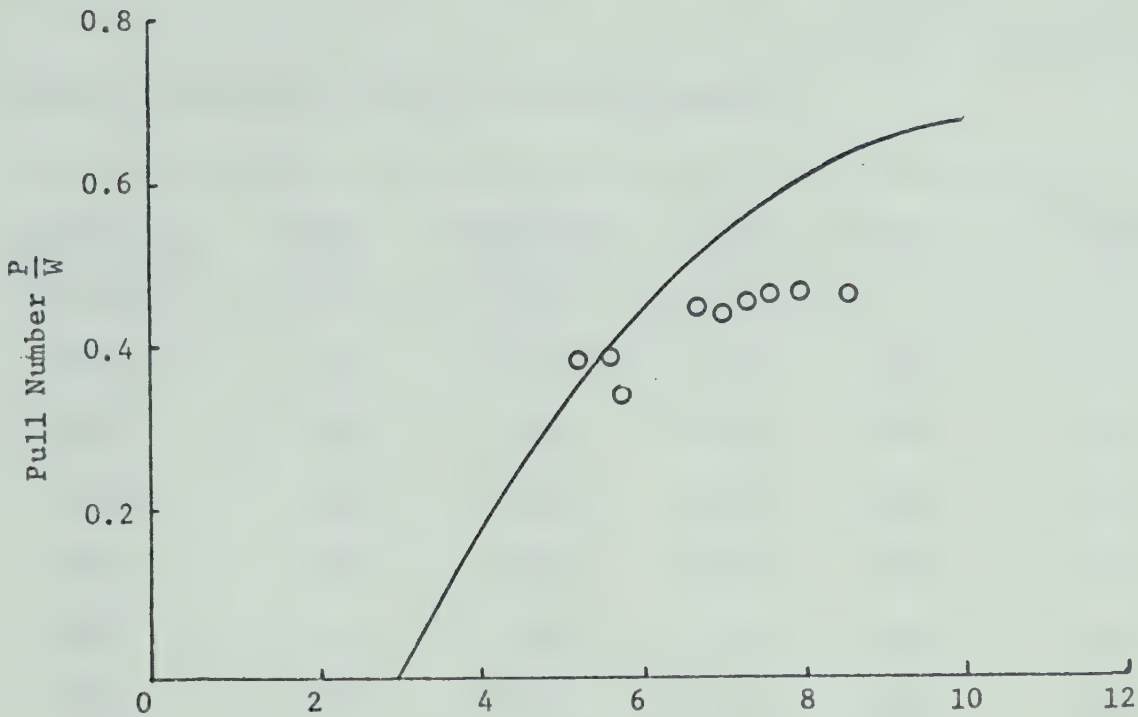
Figure 14: Relation of performance coefficients to clay mobility
number on grass surface.

The results on the stubble surface are summarized in table 3.

TABLE 3: RESULTS OF TESTS ON STUBBLE SURFACE.

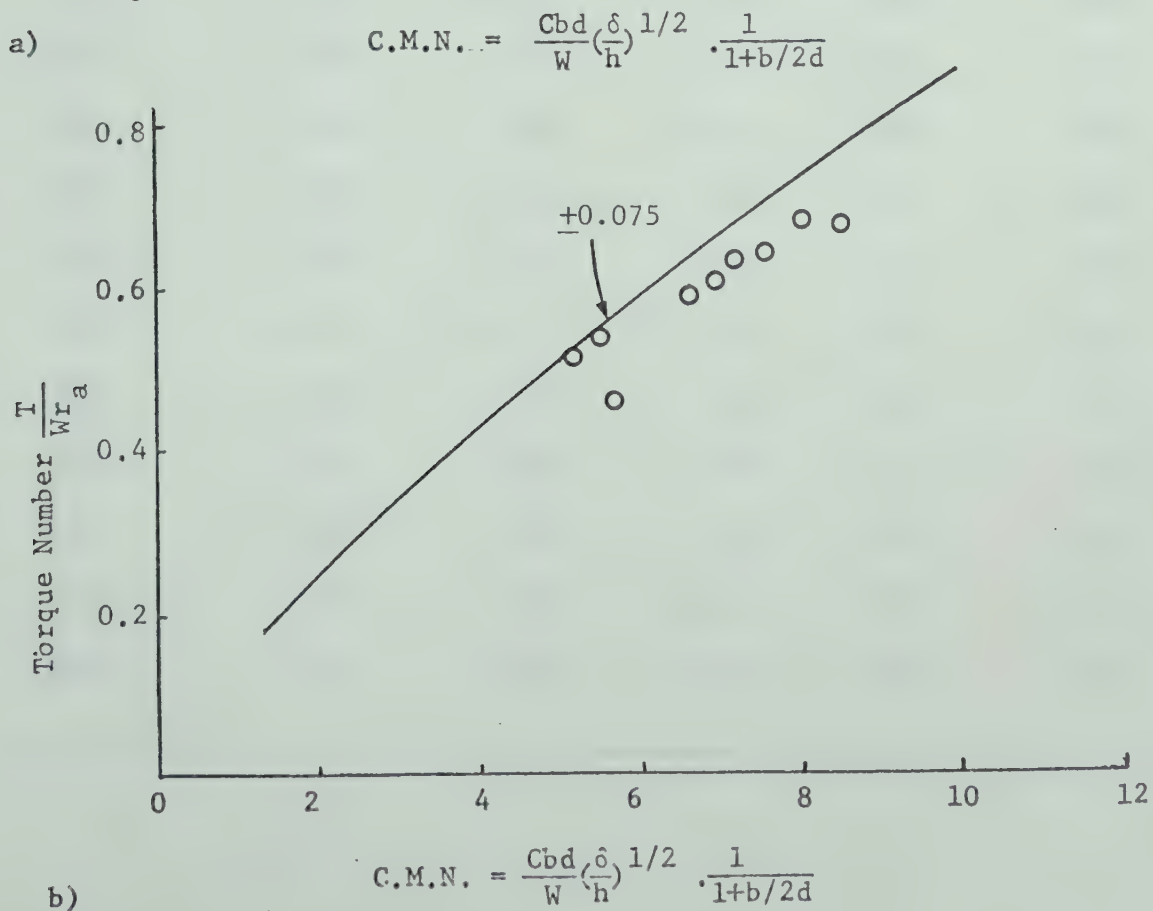| Torque on Both Wheels (lb ft)	Total Pull (lb)	Rear Wheels Weight (lb)	Pull No.	Torque No.	Clay Mobility No.
4569	1561	3867	0.40	0.63	7.61
4722	1654	3874	0.43	0.65	7.60
4792	1609	3979	0.40	0.64	7.46
5252	1774	3980	0.45	0.70	7.46
5360	1899	4659	0.41	0.62	6.74
5888	2250	4770	0.47	0.66	6.64
5675	2166	4715	0.46	0.65	6.69
5983	2029	4719	0.43	0.68	6.69
5373	1897	5526	0.34	0.53	6.06
5457	2054	5529	0.37	0.53	6.06
5650	2044	5593	0.36	0.55	6.02
6086	2222	5706	0.38	0.58	5.94
5527	2114	5844	0.36	0.51	5.85
6351	2292	5980	0.38	0.58	5.77
6569	2462	5998	0.41	0.59	5.76
6450	2511	6031	0.41	0.58	5.74
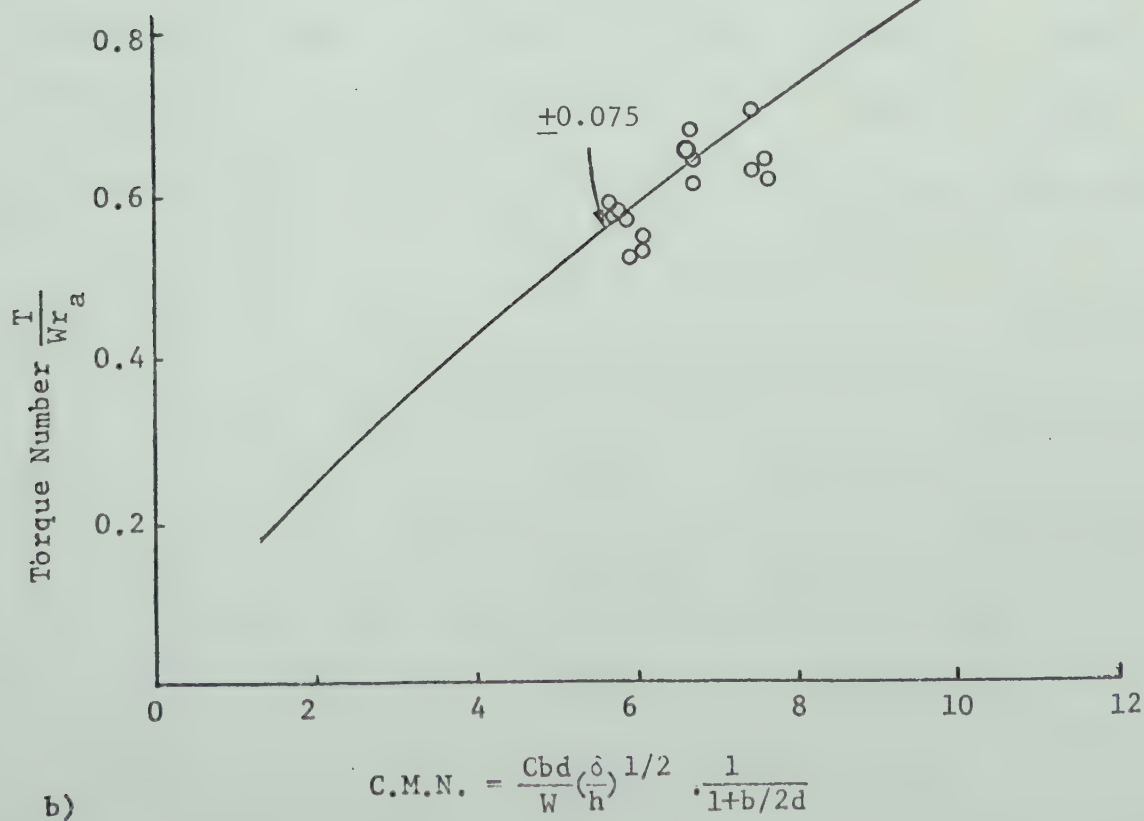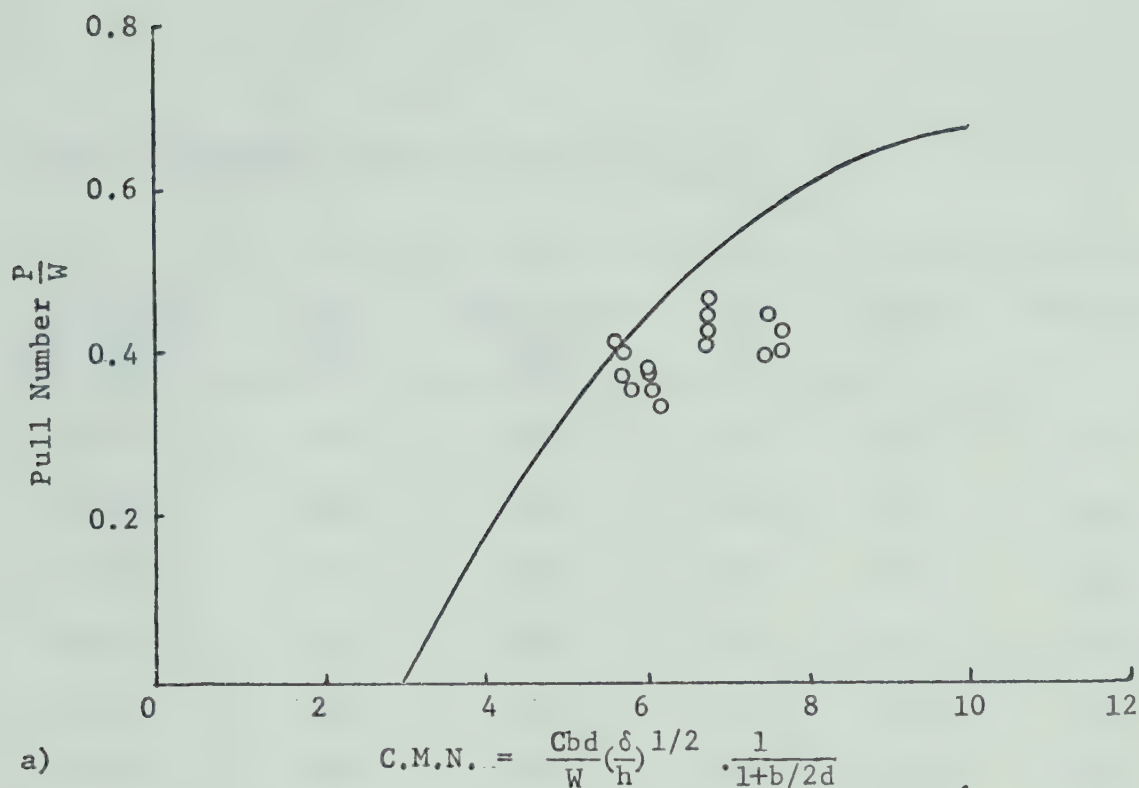
Figure 15: Relation of performance coefficients to clay mobility
number on stubble surface.

The results on the fallow surface are summarized in table 4.

TABLE 4:   RESULTS OF TESTS ON FALLOW SURFACE.

Torque on Both Wheels (lb ft)	Total Pull (lb)	Rear Wheels Weight (lb)	Pull No.	Torque No.	Clay Mobility No.
3348	951	3719	0.26	0.51	6.76
3614	1042	4140	0.25	0.47	6.31
4150	1338	4652	0.29	0.48	5.85
3893	1189	4909	0.24	0.43	5.66
5033	1618	5418	0.30	0.50	5.32
5609	1918	5897	0.33	0.52	5.05
4012	1290	6175	0.21	0.35	4.49
7307	2544	7196	0.35	0.54	3.76

44
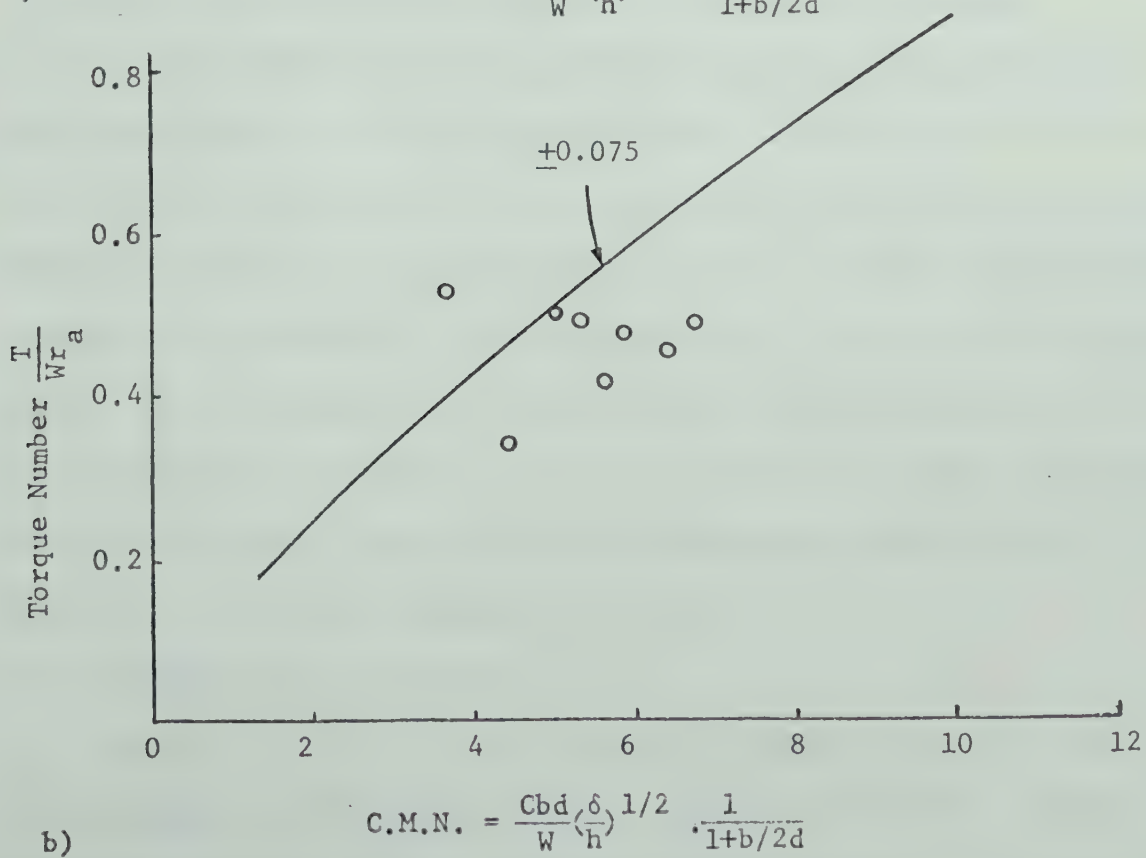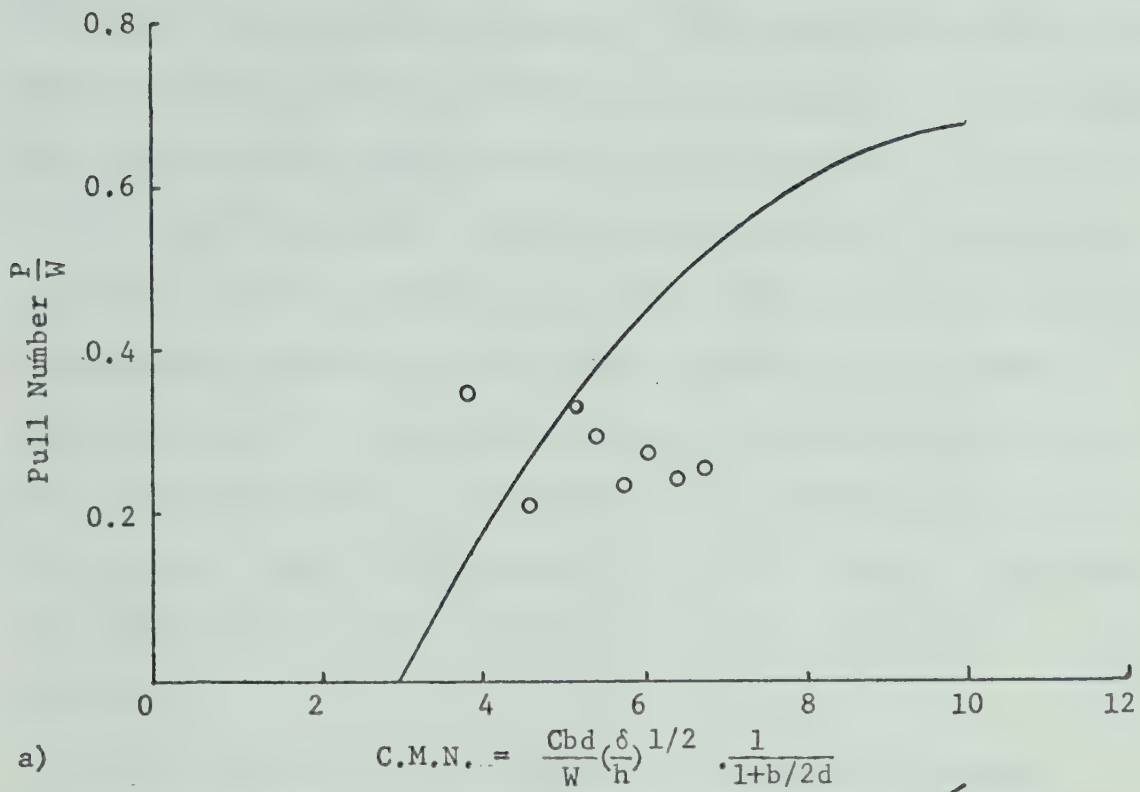
Figure 16: Relation of performance coefficients to clay mobility number on fallow surface.

The curves of figures 14a, 15a and 16a can be used for selecting tire size. First the curve between P/W (pull number) and C.M.N. (clay mobility number) should be written in equation form. By multiplying both sides by W the equation will be in the form of P. If there is an optimum load that produces maximum pull, then a plot of pull versus rear wheel load will exhibit a peak and dP/dW at that point will equal 0. Solving for dP/dW = 0, will yield an equation in the form of (W x C.M.N.) and W. Then solving the quadratic for W (i.e. W opt.) and putting this value in the equation for P optimum, both P opt. and W opt. can be found in the form of (W x C.M.N.). Hence, the optimum pull number can be found. For Freitag's curve, P/W optimum was equal to 0.455.

Now for a given set of conditions: minimum soil strength, allowable tire deflection, design wheel load, and minimum pull number (pull coefficient), tire size can be found. The equation of P/W in the form of C.M.N. can be manipulated to solve for b and d by substituting values for C,P/W opt.,W (design wheel load for one wheel) and maximum allowable tire deflection. Value of $2bd/(2d^2 +b)$ can be found in square inches. By trial and error (with different tires available on the market) tires of adequate diameter and width can be selected. Still, the final choice is arbitrary, since the tractor manufacturer must consider durability, stability and ground clearance.

6.3.2 Coefficient of Traction.

In order to evaluate the tractive performance of a soil the traction-capacity characteristics of a tractor tire must be studied. The traction capacity is characterized by the relationship between slip of the tire and its traction coefficient (17). Therefore, only the

coefficient of traction has been selected for statistical analysis. It is not valid to compare the performance at one point on the slip coefficient of traction curve. Thus the whole curve has been reduced to one slip value for comparison purposes with an analysis of covariance.

This study was part of a cooperative project between the author and another graduate student, R.D. Borg (3) whose thesis is entitled "Effect of Ballast on Traction Parameters". Borg studied the effect of ballast and speed on traction parameters for two surface conditions (grass and fallow) of Malmo silty-clay loam soil. One more surface condition (stubble) was used in this part of the study, however, the range of ballast used was not as extensive.

The analysis of covariance (Library program at the Department of Computing Science of the University of Alberta) for the coefficient of traction over three surfaces, four ballast ranges and four speeds is given in table 5.

The results have shown a significant difference (1% probability level) between surface conditions and gears. There was no significant difference between ballasts at 5% level of probability. Domier and Persson (5) also found on most of the Osborne clay surface conditions there was no or little effect of ballast on the coefficient of traction.

The means of the coefficient of traction for the different source of variations are given in table 6. The means were adjusted to a common slip value of 36% for the analysis of covariance to provide a basis for between and within treatment comparison. Thirty six percent slip was the overall mean slip of this experiment.

TABLE 5: ANALYSIS OF COVARIANCE – COEFFICIENT OF TRACTION (μ).

Source of Variation		Degrees of Freedom	Mean Square	F
Ballast	B	3	0.04415	2.681
Surface	S	2	0.52515	31.910*
	B x S	6	1.02033	62.000*
Error (1)	R/B x S	24	0.016455	
Gear	G	3	0.07455	9.677*
	G x B	9	0.00675	0.876
	S x G	6	0.0302	3.920*
	B x S x G	18	0.011796	
Error (2)	G x R/B x S	72	0.007704	

* Significant at 1% probability level.

TABLE 6:   MEANS* FOR THE COEFFICIENT OF TRACTION (μ).

Ballast Level	Grass Surface (1)	Fallow Surface (2)	Stubble Surface (3)	Average Over Surfaces
0	0.536	0.324	0.490	0.450
2	0.498	0.309	0.518	0.441
4	0.483	0.338	0.472	0.431
5	0.489	0.338	0.479	0.436
Average over Surfaces	0.501	0.327	0.490	0.457

Gears	Average over surfaces
1	0.421
2	0.443
3	0.442
4	0.452

*   The means are adjusted to 36% slip by the analysis of covariance.

For making comparisons among treatment means, especially non-independent comparisons,a Duncan's new multiple-range test was applied. This procedure can be applied on all types of variables; significant or not significant as computed by the F-value (29). The 5% probability Duncan's new multiple range test was done on the data given in table 6. The means of all the surfaces, ballasts and gears were arranged in ascending order.

Duncan's test has shown that there is no difference between the grass surface (cone index equal to 80.44 ± 14.32 lb/in.^{2}) and stubble field (cone index equal to 70.21 ± 10.37 lb/in.^{2}) but both are different from summer fallow (cone index equal to 60.87 ± 17.12) as shown in table 7 and figure 17 (obtained from regression analysis).

The statistical results (Duncan's) indicate that there is a decrease in the coefficient of traction with increase in ballast on gears and stubble field. Kliefoth (17) found that on soils with good bearing capacity and a firm subsoil, the coefficient of traction remains constant or nearly constant when tire load is changed. Kliefoth also states that on this type of soil it is possible to take the coefficient of traction constant within the range of 60 - 100% of the maximum carrying capacity of the tire and at a constant inflation pressure. Freitag (8) said on the non-frictional soil, the coefficient of traction decreases with an increase in weight and also stated that on a loose surface the slip decreased with an increase in ballast hence pull is increased at the same slip value and therefore coefficient of traction increased with an increase in the ballast.

TABLE 7:   DUNCAN'S TEST ON THE MEANS OF THE COEFFICIENT OF TRACTION (μ)

AT 36% SLIP.

a.   Surfaces

$\underline{3}$ $\underline{2}$ $\underline{1}$

b.   Ballast

| Grass | $\underline{4}$ | $\underline{5}$ | $\underline{2}$ | $\underline{0}$ |

| Summer Fallow | $\underline{2}$ | $\underline{0}$ | 4 | 5 |

| Stubble | $\underline{4}$ | $\underline{5}$ | $\underline{0}$ | 2 |

c.   Gears

$\underline{1}$ $\underline{3}$ $\underline{2}$ $\underline{4}$

Any two means not underscored by the same line are significantly different.

Any two means underscored by the same line are not significantly different.
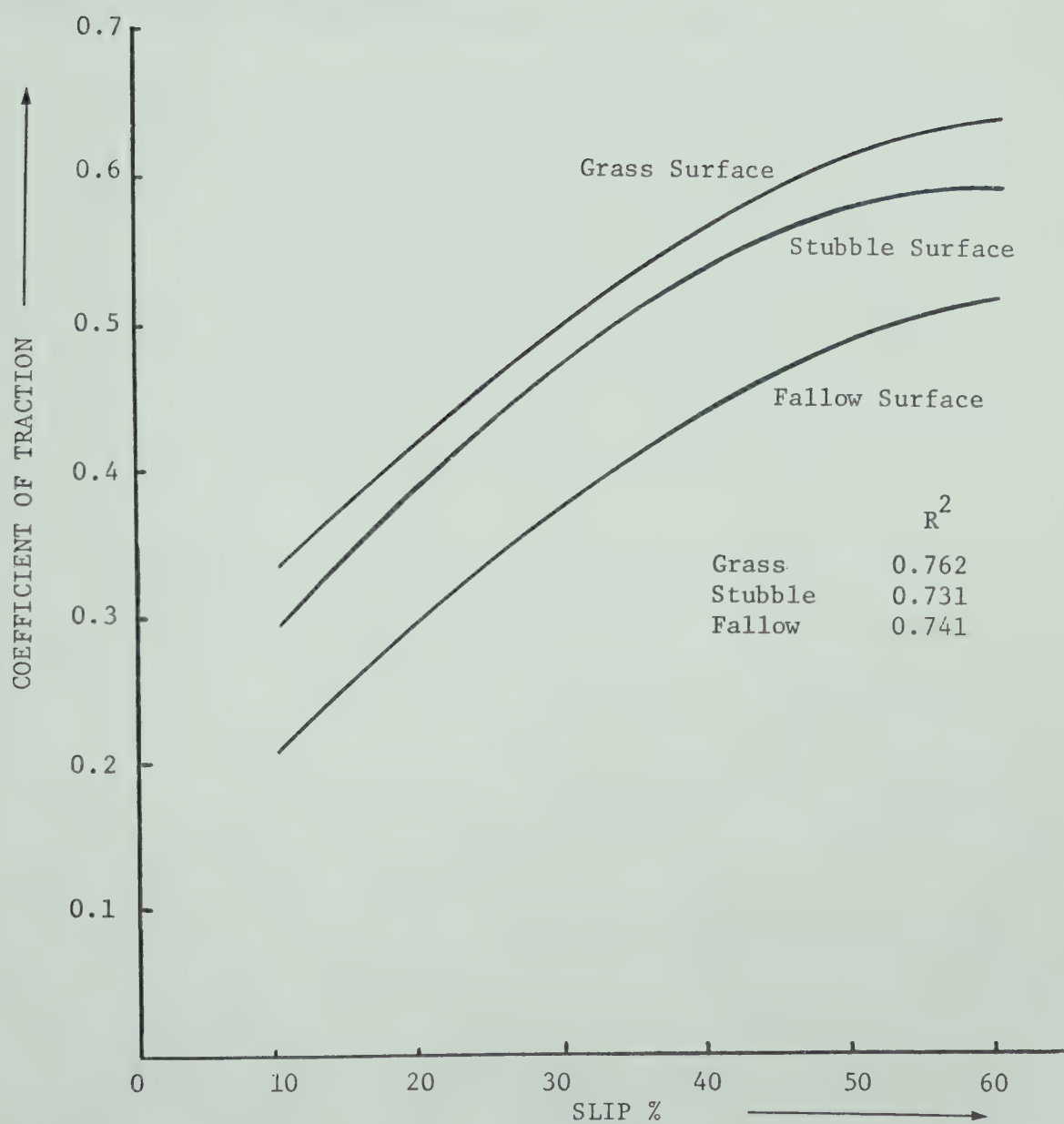
Figure 17: Coefficient of traction-slip curves for the three surfaces.

There was no significant difference (at the 5% level of probability) between the gears 2,3 and 4. The coefficient of traction for gear 1 was significantly lower, however, this is not a gear that would be used in normal field work.

7. SUMMARY AND CONCLUSIONS

The clay mobility number developed by the United States Army Waterways Experiment Station for circular and rectangular-section tires in clay can be used to predict performance on grassland and stubble surfaces of an Alberta soil (Malmo silty-clay loam).

For the fallow surface the test data do not fit the prediction curves of pull number and torque number versus clay mobility number. This could be due to several additional vehicle operating characteristics; change in wheel load due to dynamic weight transfer, steering forces, and increase in motion resistance caused by imperfect tracking wheels. The precision of prediction of wheeled vehicle performance in the field suffers, since far less control can be exercised there than in the laboratory.

An analysis of covariance of the coefficient of traction for three surfaces indicated that there was no significant difference between the grass surface and stubble surface. The fallow surface had the poorest traction characteristics. On the firm surfaces (grass and stubble) the coefficient of traction decreased with an increase in ballast. On the loose surface (fallow) an increase was observed.

For the field speeds used in the study, speed had no apparent effect on the coefficient of traction.

Of the soil physical properties measured the cone index has additional merits over others. Cone index is a good measure of soil consistency and a direct indicator of soil traction characteristics.

8. RECOMMENDATIONS FOR FUTURE WORK

1. The time response of all the transducers should be taken into consideration.

2. The possible use of data acquisition systems (tape recorder, etc.) and analog computers to give slip-coefficient of traction on an x-y recorder should be considered.

3. The test area should be pre-tested for cone index to reduce the variation in field conditions.

4. More data should be collected at low slip values to get the proper shape of the slip-coefficient of traction curve.

5. Other typical Alberta soils should be characterized for traction.

6. If possible, liquid ballast should not be used in the tires as it is difficult to reduce the pressure.

7. To accurately determine the relationship between performance coefficients and a single dimensionless term (consolidation of soil and tire parameters) for a particular soil, a series of tire sizes and deflections should be studied over a wide range of cone index (for the same surface condition).

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APPENDICES

APPENDIX 1: SOIL AND SOIL-MATERIAL PROPERTIES.

Soil Properties	Symbol
Cohesion	c
Friction angle	ϕ
Viscosity	η
Density	ρ_d
Wet unit weight	γ
Coefficient of compressibility	m, n_c, b_c
Tensile strength	T_s
Modulus of elasticity	E
Modulus of rupture	R
Grain size	r
Adhesion	δ_a

Soil-material friction angle
Soil-material property $\quad A_a$

(Soil-material adhesion).

APPENDIX 2: CLASSIFICATION OF SOIL-MEASURING DEVICES.

Test or Device	Measurements	Derived Output
Triaxial	stress, strain, time	$c, \phi, \eta, m, n_c, b_c, E$
Unconfined compression	stress, strain, time	qu
Direct shear	stress, strain, time	c, ϕ, n
Ring shear	torque, angle, load, rate of rotation, sinkage	c, ϕ, n, k
Sheargraph	torque, load	c, ϕ
Shear vane	torque, angle	c, S
Plate penetration	pressure, sinkage, time	$k_c, k_\phi, n, k_c', k_\phi',$ c, n, C_r
Tilting plate Penetrometer	horizontal and vertical forces, horizontal and vertical displacements	$H/Q, x/l$
Cone penetrometer	sinkage, time	C, PR, c, n, G
Vibratory test	frequency amplitude, phase	n, E
Tension test	axial load	T_S
Beam loading	load	R
Nuclear devices	counts	γ, ρ_d
Samplers	volume, weight	γ, ρ_d
Particle-size test	percent passing	r

APPENDIX 3: WHEEL GEOMETRY.

For off-road vehicles terms used in this study with special meanings are defined as follows.

1. Diameter (d). - Outside diameter of the inflated but unloaded treadless tire.

2. Sectional width (b). - Maximum outside width of the cross section of the inflated but unloaded tire.

3. Section height (h). - Distance from the lip of the rim flange to the periphery of the treadless tire.

4. Deflection (δ). - Difference between the section height and the loaded section height.

5. Nominal rim diameter. - Diameter measured from shoulder to shoulder of the rim.

6. Rim diameter. - Diameter measured from the lip of the rim flange to the opposite lip of the rim flange.

Pneumatic tire terms.
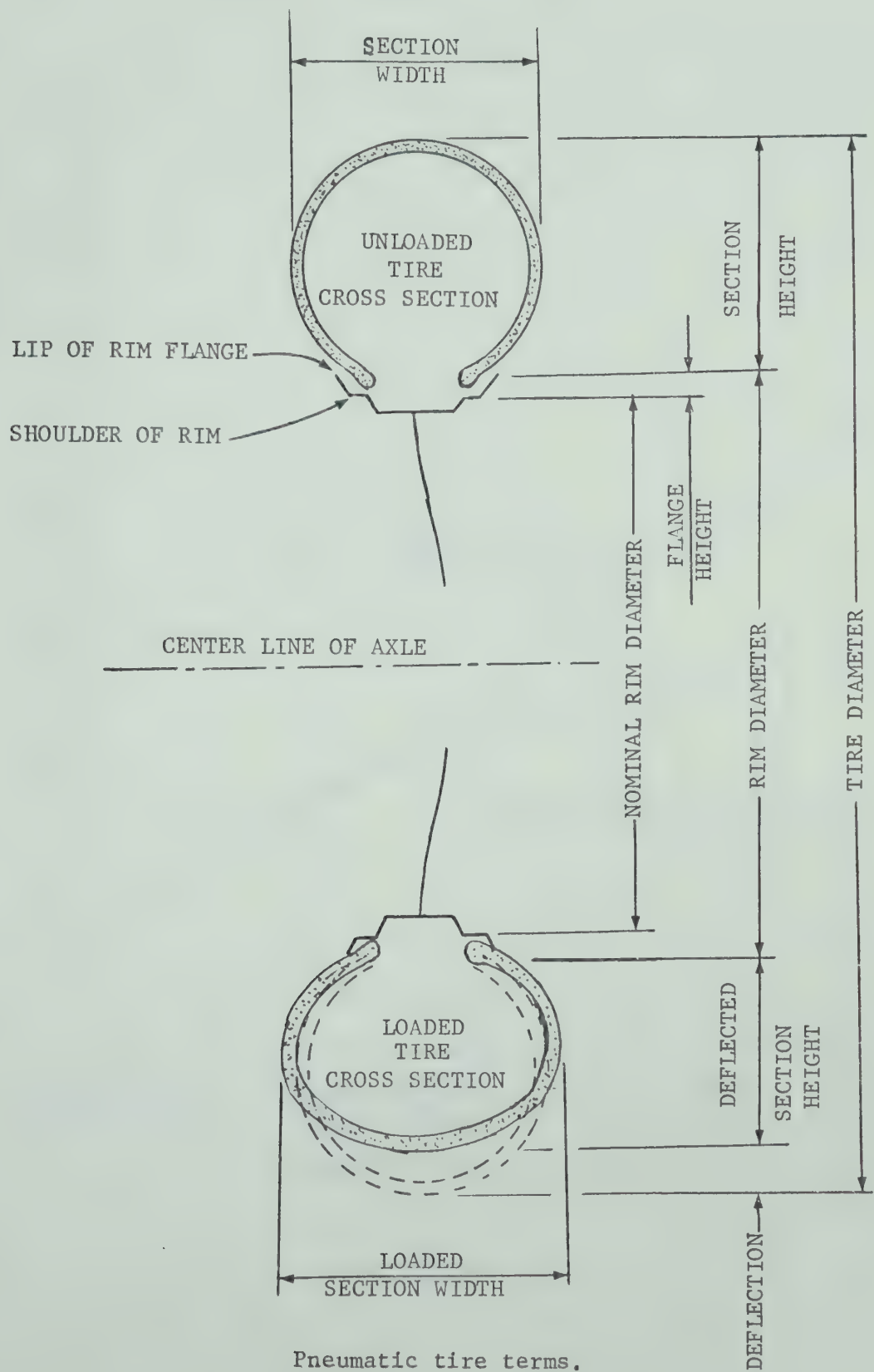
APPENDIX 4: EFFECT ON $\frac{2bd^2}{2d+b}$ CAUSED BY CHANGING THE VALUES OF b AND d.

Effect on $\frac{2bd^2}{2d+b}$ of changing d

Effect on $\frac{2bd^2}{2d+b}$ of changing b

VALUES OF $\frac{2bd^2}{2d+b}$ RELATIVE TO A VALUE OF 1.0K for b = 1.0 and d = 1.0.

b=0.5, d=1.0	b=1.0, d=1.0	b=1.5, d=1.0	b=2, d=1.0
b=1.0, d=0.5	b=1.0, d=1.0	b=1.0, d=1.5	b=1.0,d=2.0

RELATIVE VALUES OF b and d.
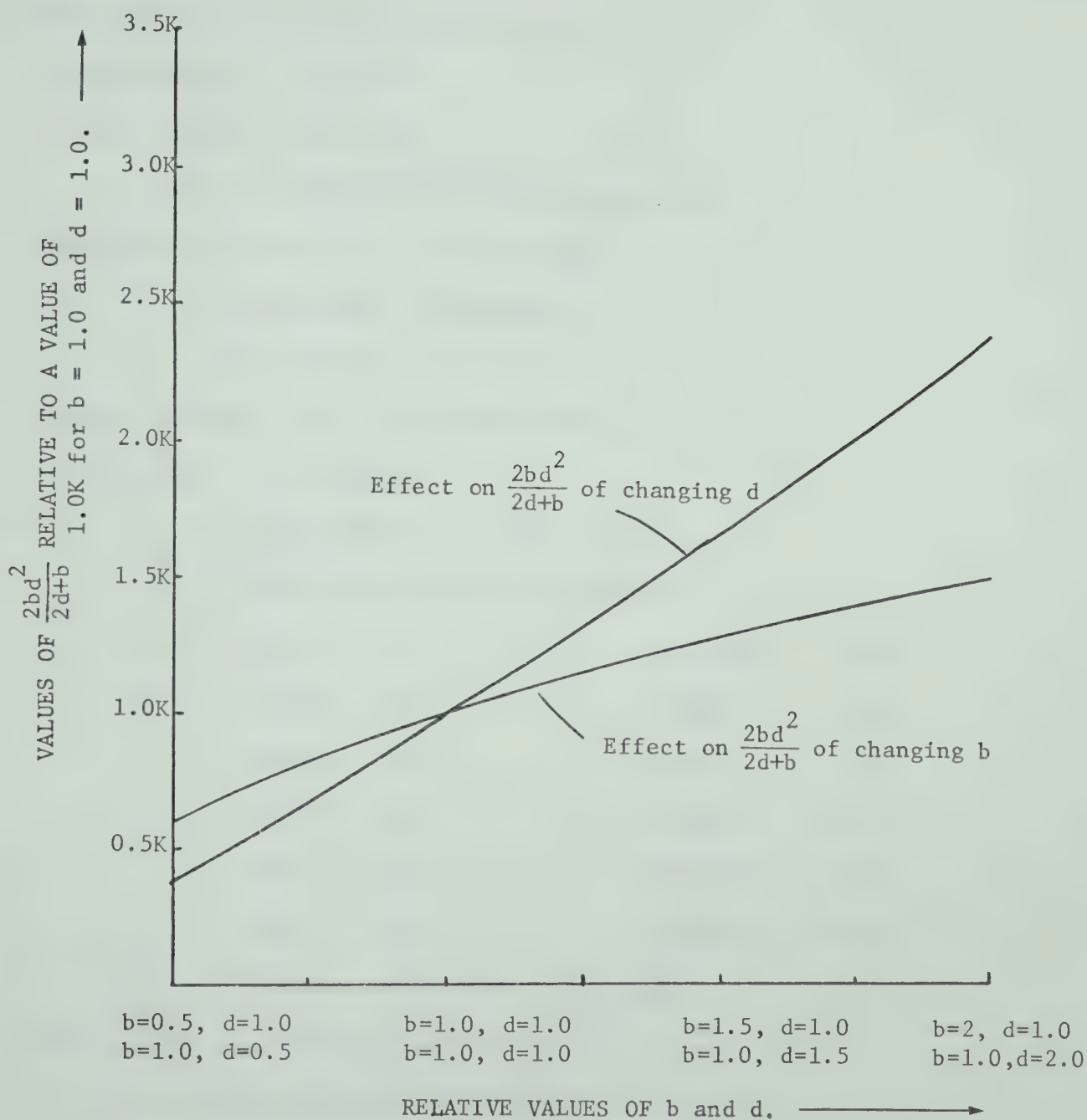
APPENDIX 5:   SPECIFICATIONS OF THE TEST TRACTOR.

Make and Model: Massey-Ferguson MF-135

Serial Number: 9A II5375

Weight: Front -- 1530 lbs.

        Rear -- Variable from 2530 to 6390 lbs.

Dimensions: Wheel base -- 72 3/8 inches

        Front tread -- 60 inches

        Rear tread -- 56 inches

Engine: Perkins. AD3. 152 Diesel Model

Transmission: Multi-Power

        12 Forward and 4 Reverse speeds.

        Rated Speed (M.P.H.) at 2000 RPM.

First	1.31	Seventh	5.24
Second	1.71	Eighth	6.85
Third	1.97	Ninth	7.85
Fourth	2.56	Tenth	10.09
Fifth	3.60	Eleventh	14.40
Sixth	4.70	Twelfth	19.49

        Reverse: 1.79, 2.33, 7.14, 9.13.

Tires: Front   6.00-16, 4 ply rating

      Rear   14.9/13-24, 4 ply rating.

APPENDIX 6:   SOIL PROPERTIES (0 to 6 inches, average).

1.   Grass Surface

Properties

Dry Density	54.95 ± 8.04 lb/ft^3
Bulk Density	68.84 ± 8.82 lb/ft^3
Moisture	25.61 ± 4.71 %
Moisture Content*	28.86 ± 4.33 %
Cone Index	80.44 ± 14.32 lb/in.^{2}
c**	0.64 ± 0.07 lb/in.^{2}
ϕ	33.39 ± 2.37 degrees

2.   Fallow Surface

Dry Density	42.83 ± 5.23 lb/ft^3
Bulk Density	53.91 ± 5.66 lb/ft^3
Moisture Content	26.28 ± 6.70 %
Moisture Content*	26.72 ± 4.63 %
Cone Index	60.87 ± 17.12 lb/in.^{2}
c*	0.35 lb/in.^{2}
ϕ	34.5 degrees

3.   Stubble Surface

Dry Density	43.11 ± 4.76 lb/ft^3
Bulk Density	55.10 ± 4.15 lb/ft^3
Moisture Content	28.22 ± 4.23 %
Moisture Content*	17.77 ± 1.25 %
Cone Index	10.37 ± 10.37 lb/in.^{2}
c**	0.62 ± 0.17 lb/in.^{2}

APPENDIX 6:   Continued

ϕ 40.63+0.95 degrees

*   This is the moisture content determined by the standard gravimetric

procedure.

**   The values of c and ϕ are only for the top 1 cm.

APPENDIX 7:   MECHANICAL ANALYSIS OF TEST SOIL.
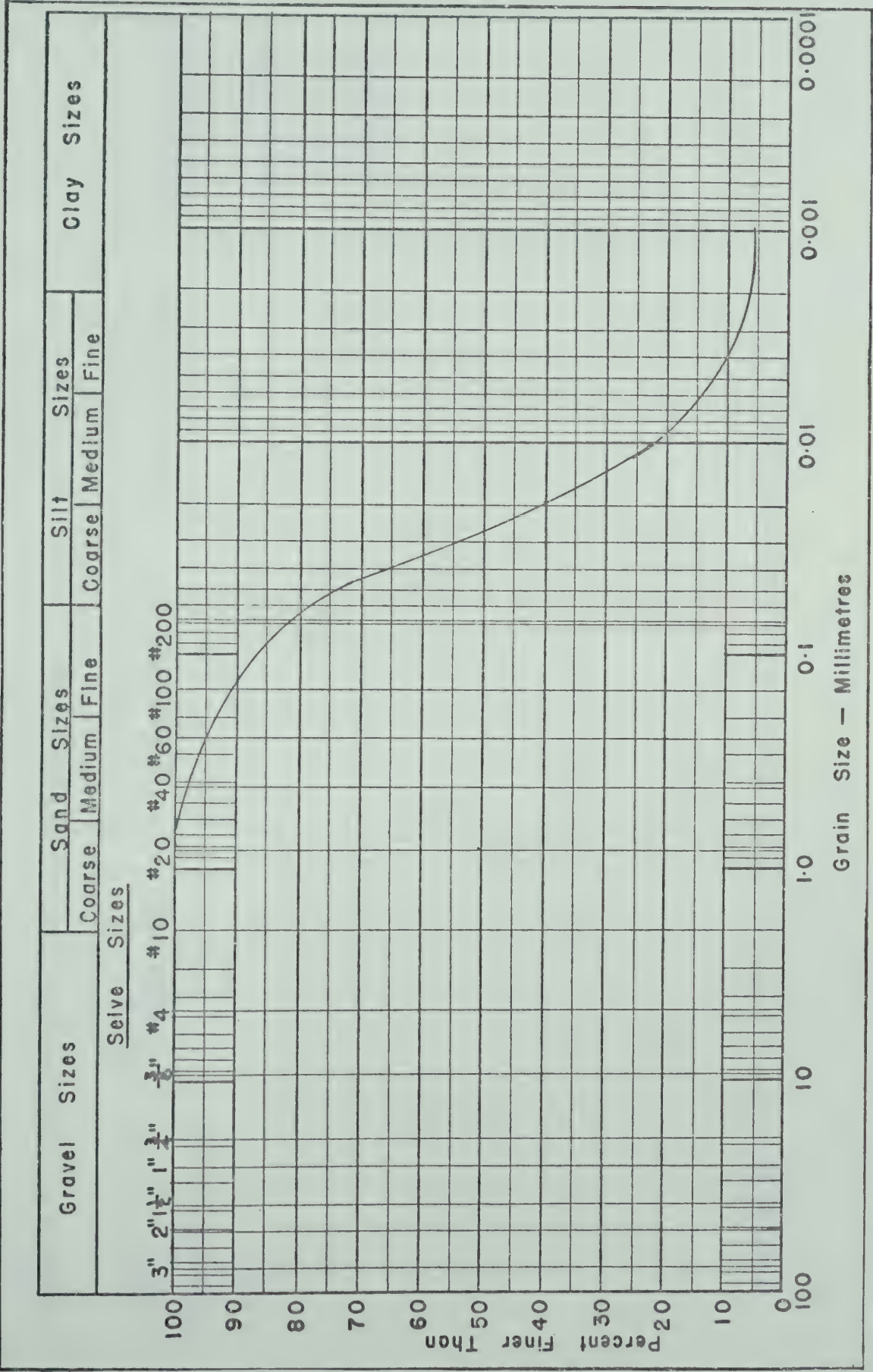
APPENDIX 8: CLASSIFICATION TEST DATA FOR TEST SOIL.

Soil	Liquid Limit	Plastic Limit	Plasticity Index	Classification*
Malmo silty-clay loam	39.5	30.6	8.9	OL (organic silt-clay of low plasticity.)

* This classification is according to Unified soil classification (17).